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STUDIES OF COST EFFECTIVE STRUCTURES DESIGN FOR FUTURE SPACE SYSTEMS - SUMMARY

by Bruce Allesina and E. F. Styer

Prepared by
THE BOEING COMPANY
Seattle, Wash.
for

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PREFACE

This final report presents the results of a 1-year study conducted between October 17, 1966, and October 17, 1967, for Headquarters, National Aeronautics and Space Administration, Office of Advanced Research and Technology. Work was accomplished under Contract NAS7-525, which was released under the NASA OART Space Vehicle Structures Program, and is based on Boeing-sponsored research in cost effective design.

The study was performed by The Boeing Company, Space Division, Advanced Spacecraft Systems organization. E. F. Styer supervised the program. Bruce Allesina, the principal investigator, was assisted by George E. Woodhead, who was responsible for weights analysis and cost technology. Technical participants were D. W. French, J. S. Guarre, J. C. McGinnis, S. L. Rieb, and L. M. Benson.

The authors wish to acknowledge the contributions of M. T. Braun, C. P. Martin, and P. L. Peoples, all of Boeing.

Backup information will be found in the companion document, *Final Report on Studies of Cost Effective Structures Design for Future Space Systems---Backup*, D2-114116-2.

FOREWORD

This document has a format that may be new to some readers. The technical content is divided into three parts: "Tools for Economic Analysis," "Structures and Materials Studies," and "System Studies." Each part is then subdivided into section headings according to individual study tasks. Subjects are then divided into topics; each topic presents a particular idea, which is stated concisely in a proposition statement set off from the text that supports it. Thus, the format produces a more readable document, provides easy access to information, and permits major study results to be summarized without loss of important data. Readers who may be unfamiliar with the concepts of economics in engineering are encouraged to scan all the proposition statements (set in script) before reading the document in detail.

CONTENTS

1.0 INTRODUCTION AND SUMMARY

1.1 ACCOMPLISHMENT OF CONTRACT GOALS

At its inception, three major goals were established for this contract effort. First, define promising directions for structural research by applying the concept of minimum cost rather than maximum performance to structural design. Second, understand the relationship of structure to the economics of the total system. Third, identify and apply the interactions of the various aspects of program costs to point out the potential cost savings they imply.

The material presented in this report shows that these goals have been satisfied. A number of structural research areas have been identified. These are developed individually throughout this document and are collected in this section for visibility.

An understanding of the system role played by structure has been developed in five system studies that show, in general, that structure, when considered as a subsystem, is unique in its far-reaching effect on the system. Moreover, detailed consideration of other subsystems reveals a large structural influence.

Finally, strong interactions of structural design decisions with aerospace system costs have been demonstrated, particularly by the study described in Section 4.5, and significant potential cost savings have been identified.

1.2 SCOPE OF EFFORT

Studies with limited scope can produce only limited benefits, regardless of how well or to what depth they are conducted. This is true in conventional trade studies where a specific subsystem may be optimized, but its impact on the system may dictate no gain or even a net performance loss. It is particularly true of cost effectiveness studies because program cost interactions are so strong.

Since this study represented a relatively small attack on a very large subject, detailed technical trades were specifically avoided, and effort was concentrated on considering system cost aspects to ensure identification of major cost contributions. The results, in terms of the information presented in Section 4.0, show that this approach was justified.

1.3 OUTLINE OF DATA

The discipline of engineering demands an orderly approach to achieve quantitative answers to design questions. This approach requires the establishment of valid basepoint data, the development of analytical tools, the demonstration of the workability of these tools, and finally, the application of these tools to solve specific problems. Because minimum cost design in engineering is a relatively immature discipline, all of the above steps had to be considered and fresh developments made in each area.

Development of tools for economic analysis was necessary to resolve raw cost data into systematic forms and to derive the important characteristics from this data. Analytical methods of handling and applying cost data were required to permit rapid solution of design problems.

Specific structure and material areas were exercised using economic tools to develop familiarity with the methods and to provide a check on workability. These areas served as test cases to show that adequate cost data can be found and that valid results can be realized by applying minimum cost techniques to advance aerospace design areas.

Since, as has been shown, contract goals could be satisfied only by studying systems, a number of such studies were conducted. These studies covered as many critical areas of the future space program as could be encompassed within the scope of the contract.

1.4 LIMITATIONS OF INFORMATION

Specific studies discussed in subsequent sections, which depend upon absolute cost data, can produce results that are only as good as the cost assumptions on which they are founded. Although the cost data that has been used is the best available in open literature and has been carefully screened, the nature of cost information is such that it relies heavily on accounting systems and can be slanted to achieve specific ends. Moreover, raw cost data possesses a high level of scatter that can be resolved statistically only with a large sample, but in many cases a large sample of data is unavailable.

In contrast, the tools for economic analysis and the approaches taken in making cost studies are not subject to assumptions beyond the normal ones of neglecting second-order effects and have wide validity.

1.5 SUMMARY OF RESEARCH IMPLICATIONS

Application of economics to aerospace design problems has yielded a number of system conclusions and implications for structural research that are characterized by being different from those reached with maximum performance designs. These are developed throughout the document and are summarized here.

General implications are:

1) Cost considerations should be employed early in a program while there is still time to effect major program decisions.
2) A concerted program of cost data collection, economic methods development, and industry education in the use of cost as a design criterion is required.
3) The achievement of economics in aerospace programs depends heavily on establishing the proper balance between costs and weights for design candidates at the part, subsystem, and system level.
4) There should be a de-emphasis of sophistication in low-Earth-orbit payloads; emphasis should be placed on the use of larger launch vehicles.
5) For high-energy missions (integrated velocity change greater than 30,000 ft/sec), payload design sophistication is economically justified, particularly in structural components.

6) There should be research toward a better understanding of the role of structure in total system and in "nonstructural" subsystems.

7) Commonality (a single multimission design) is a powerful economic requisite for advanced space programs.

8) Space mission environments must be better defined. Potential program savings justify extensive expenditure in this area.

9) Space program testing philosophy should be defined on a cost effective basis, measured against mission risk.

10) Contract studies indicate:

    a) Thermal protection system selection depends on vehicle and mission configuration. All concepts should be researched, but emphasis should be placed on systems for low to medium L/D vehicles;

    b) The most easily fabricated materials are cost effective at transportation margins below $100/lb, and least-weight materials are cost effective at margins above $1000/lb;

    c) The marked superiority of a soft-shell over a hard outer shell concept for small-quantity LH_2 containment in space;

    d) The cost effectiveness of relatively low-strength low-cost steels, such as HY-150, in high-pressure tankage for lower stages of launch vehicles.

Specific implications are:

1) A new, two-stage Earth launch vehicle would be economically justified to cover the payload range between Titan III and Saturn V for a viable space program. LOX/RP-1 new stages, and existing stages, should be investigated for this new vehicle.

2) Manned space exploration requires continued development and uprating of the Saturn V and intensified study of an economical Nova-class launch vehicle.

3) Most manned Earth entry vehicle requirements are best satisfied by a configuration having low to medium hypersonic L/D (L/D less than 1.5). Research for such a vehicle should stress design for multiple mission use and reusability.

4) Common hardware elements---space mission module, space propulsion module, Earth return vehicle, and a larger-than-Saturn V Earth launch vehicle---are all economically indicated for manned space exploration. Other mission functions should be further studied to find their economic solutions.

5) Modularizing planetary propulsion stages so that IMIEO is minimized does not minimize program cost.

2.0 TOOLS FOR ECONOMIC ANALYSIS

Need for Economic Tools

The use of cost in planning aerospace programs requires the development of quantitative methods for economic analysis.

Although a body of cost data exists, there is a general lack of understanding of why elements cost what they do and what elements act to make up total program costs. Costs have been estimated, at least as part of contract negotiations, for every past hardware program, but the estimating procedures have been long, detailed, *ad hoc* exercises occupying many manhours. This pricing approach parallels that of a detailed weight and performance analytical study conducted for a hardware item---a dress rehearsal---prior to the actual hardware program.

System studies that are intended to examine major aspects of aerospace programs cannot afford the time and effort of *ad hoc* cost estimation, which, to be accurate, must be carried to a fine level of detail. To speed the process of cost estimation without loss of accuracy, systematic methods of cost prediction are therefore required that, by being based on "top level" costs, automatically encompass program details. Again, there is a parallel between these methods and weight prediction techniques that have been developed in response to similar needs.

The tools to be developed, so that regularized systems studies may be conducted, must include methods of basic cost predictions, methods of screening concepts, methods for considering the effect of weight on cost, and methods for combining operational costs such as recovery and maintenance.

Necessity for Developing "Economics Engineers"

Cost technology is a new field and one in which engineers must become trained.

The use of trend data to make trades at early program levels introduces the possibility of reaching erroneous conclusions by poor choice of ground rules. All program aspects cannot be fully considered in a typical study; therefore, choosing important aspects (that is, those that influence the answer) is a matter of sound judgment. This judgment can be developed only by the experience and discipline of a functional organization. The previously noted parallel of cost with the weights discipline is again apparent in that weight prediction techniques, with the same uses and misuses, have progressed through the same evolution. Their success shows that cost prediction techniques can become commonly accepted if cost engineers are developed who have experience and abilities that match those of today's weights engineers.

Economic Areas Studied

Cost technology, transportation costs, concept selection technique, and system/subsystem cost optimization technique (SCOT) were necessary to permit general economic analysis, while configuration by economic analysis is a technique developed in response to a specific economic problem.

To apply economics to a space system, specific developments were required to provide a data base and tools for rapid analysis. A cost data base, described in Section 2.1, "Cost Technology," was required to evaluate and predict the true costs of various program elements. The concept of transportation costs was necessary to permit rapid and correct economic valuation of weight. The concept selection technique provides an economic method for screening of design alternatives, which is vital in early program phases to reduce the number of concepts to a manageable level. SCOT provides a needed tool for achieving the proper balance of cost and weight.

Configuration by economic analysis was required in the proper assessment of recoverable booster economics and illustrates the development of economic tools for specific design problems.

2.1 COST TECHNOLOGY

Need for Cost Prediction Techniques

The ability to predict costs of various elements of future space programs is necessary to influence program planning at all levels.

To make engineering decisions in program planning based on cost implies the knowledge of cost values and the availability of choices between cost alternatives. If costs are known for each program element as related to its technical characteristics, the influence of these characteristics on program cost can be determined, and the resulting least cost option can be recommended. Thus, data must be available that relate costs to the various engineering aspects of programs for which trades are considered.

The Choice of Historical Data Trends or Synthesized Costs

Although costs for space program elements can be synthesized through step-by-step estimation, it is better to predict costs from historical data for similar elements because this technique accounts for unplanned cost aspects.

Predicting costs by synthesis has shown itself to be inaccurate. Figure 2.1-1 is a plot of actual cumulative costs and original contract estimates for the Lunar Orbiter vehicle. The cost growth shown for this program is small when compared to that for other hardware programs.

It is this characteristic of synthesized costs---that they are low compared to actual costs---that makes the use of historical cost data a better method of cost prediction because the historical data will already have cost growths included for whatever reason they occur.

The restriction on using historical costs is that the data must be comparable; that is, the data must represent programs for similar hardware, the same aspects of each program must be considered, the same program phases must be included, dollar values must be normalized to a common year, and the relative technical nature of the programs (state of the art) must be the same.

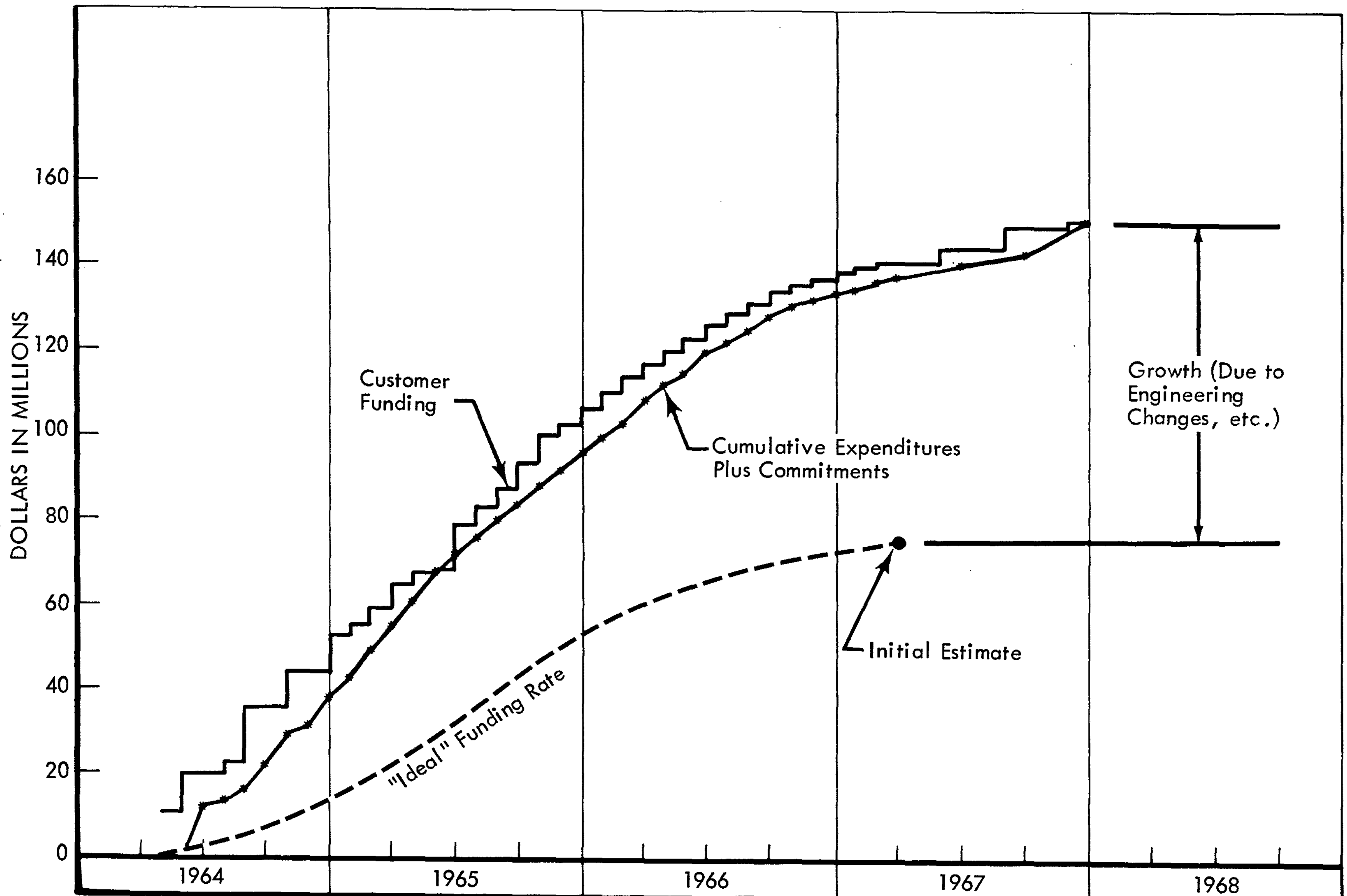


Figure 2.1-1: LUNAR ORBITER PROGRAM
Total Program Funding and Expenditures (Fee Excluded)

Establishing Nonrecurring and Recurring Costs

To predict costs adequately, it is necessary to distinguish costs that are incurred only once (nonrecurring) from those incurred each time a new hardware unit is processed (recurring) because each element behaves differently.

Hardware programs rarely have a clean contractual break between those costs necessary to develop the hardware and those costs incurred in producing operational hardware. Therefore, the division between nonrecurring and recurring costs is artificial from the standpoint of actual dollar spending. Care is required to separate one type of cost from the other, and what is a nonrecurring cost in one program can be a recurring cost in another (e.g., ground support equipment for the Lunar Orbiter and the Minuteman).

A distinction must be made between these two types of costs because they are affected by different aspects of the hardware and, thus, show different trends. Figures 2.1-2 and 2.1-3 illustrate this difference for launch vehicle stages (less engine subsystem). Note that recurring costs are much more affected by weight than are nonrecurring (development) costs.

Learning Curves

The effect of learning on the cost of manufacturing multiple units of hardware must be considered any time more than three or four units are processed.

The ability of production workers to learn, and thereby improve their cost performance for repetitive operations, is illustrated by the steady decline in fabrication time (and therefore cost) as more units of hardware are produced. This learning is displayed in Figure 2.1-4, which plots production manhours for the Bomarc B. The curve illustrates the lack of a definite trend to costs of the first few units, which results from working out "bugs" in the production line.

The learning process is characterized by straight lines on log-log plots of production cost as a function of unit number. Such lines are commonly

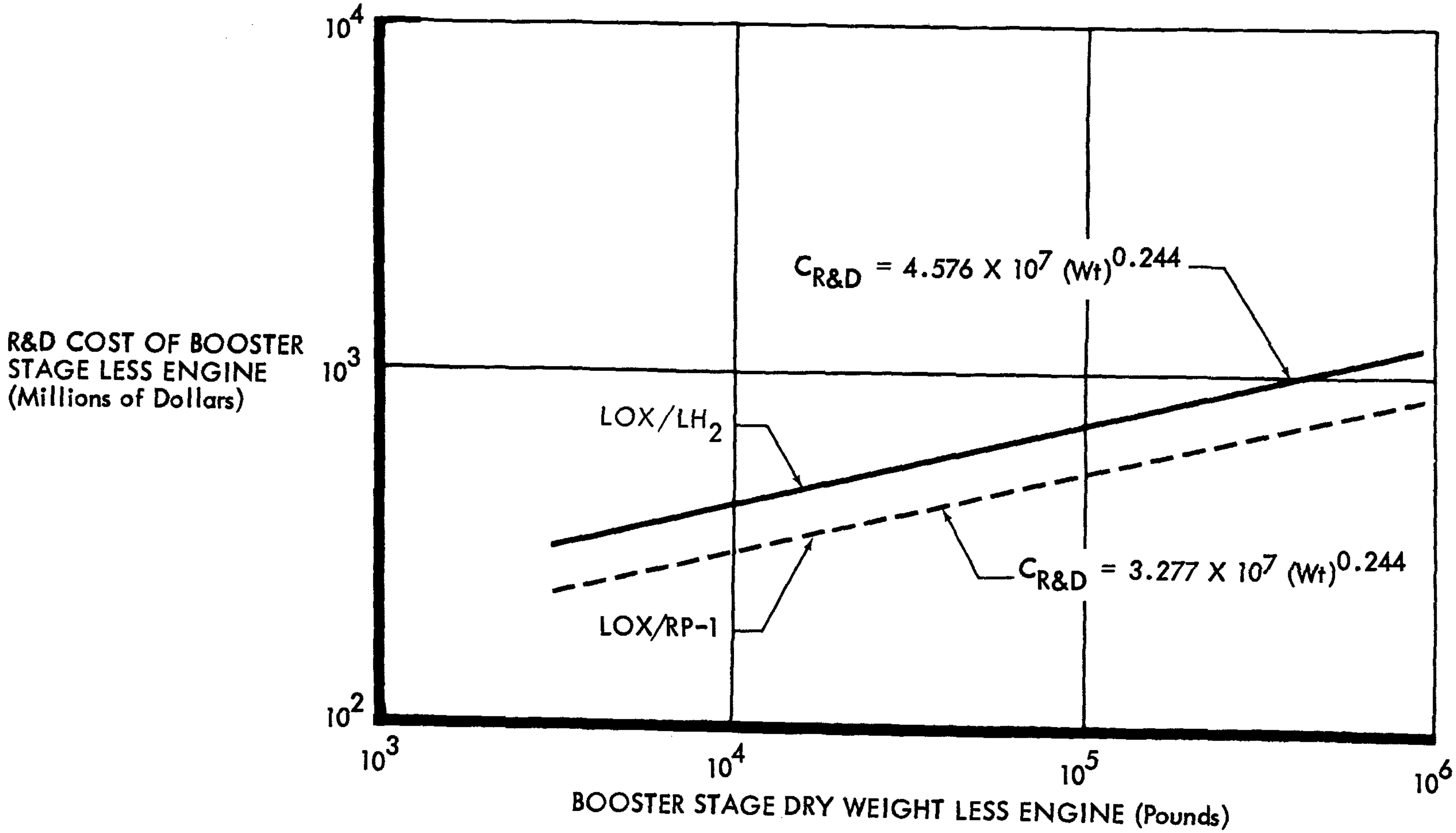


Figure 2.1-2: LAUNCH VEHICLE DEVELOPMENT COSTS -- *Stage Less Engine*

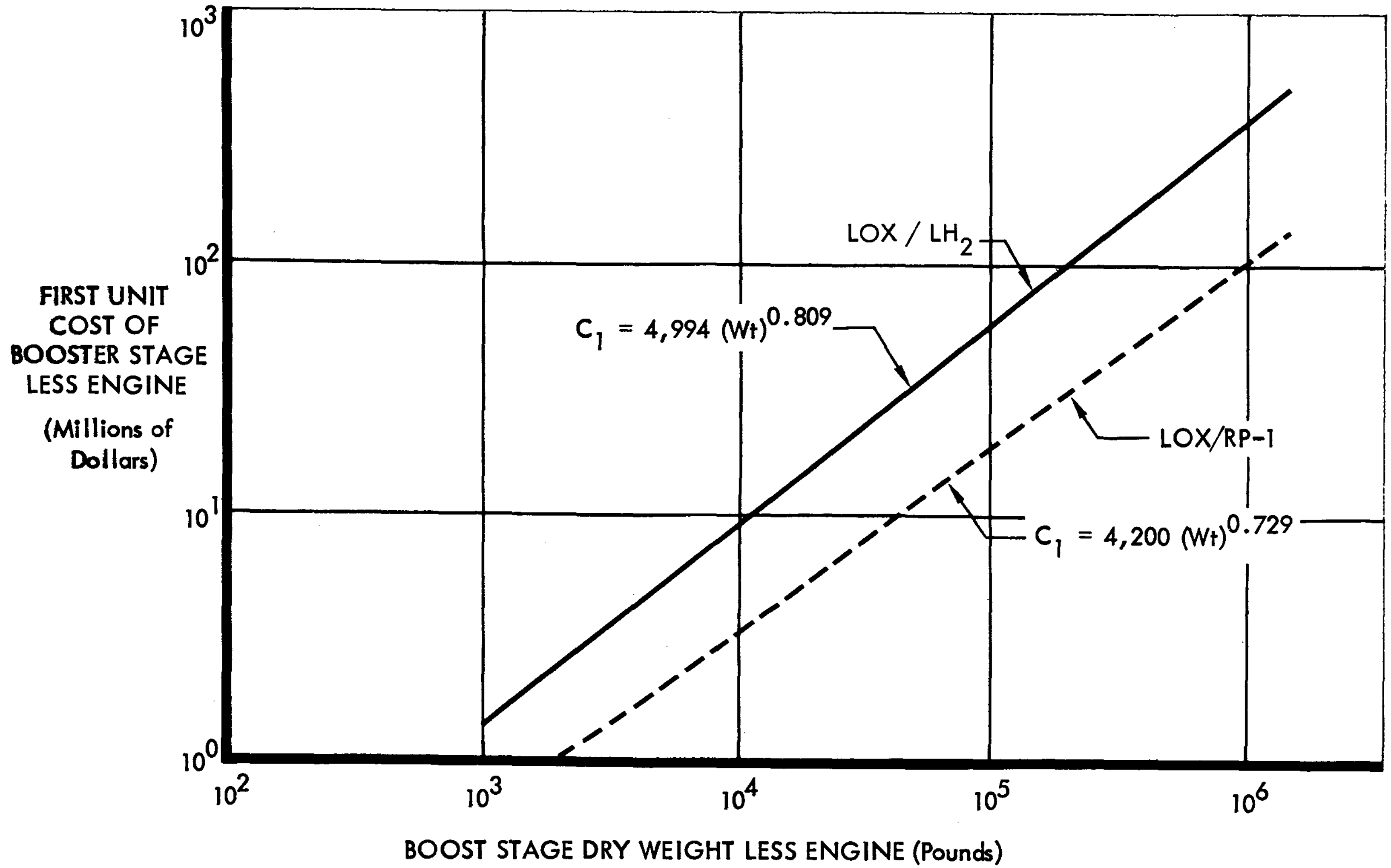


Figure 2.1-3: LAUNCH VEHICLE RECURRING COSTS -- Stage Less Engine

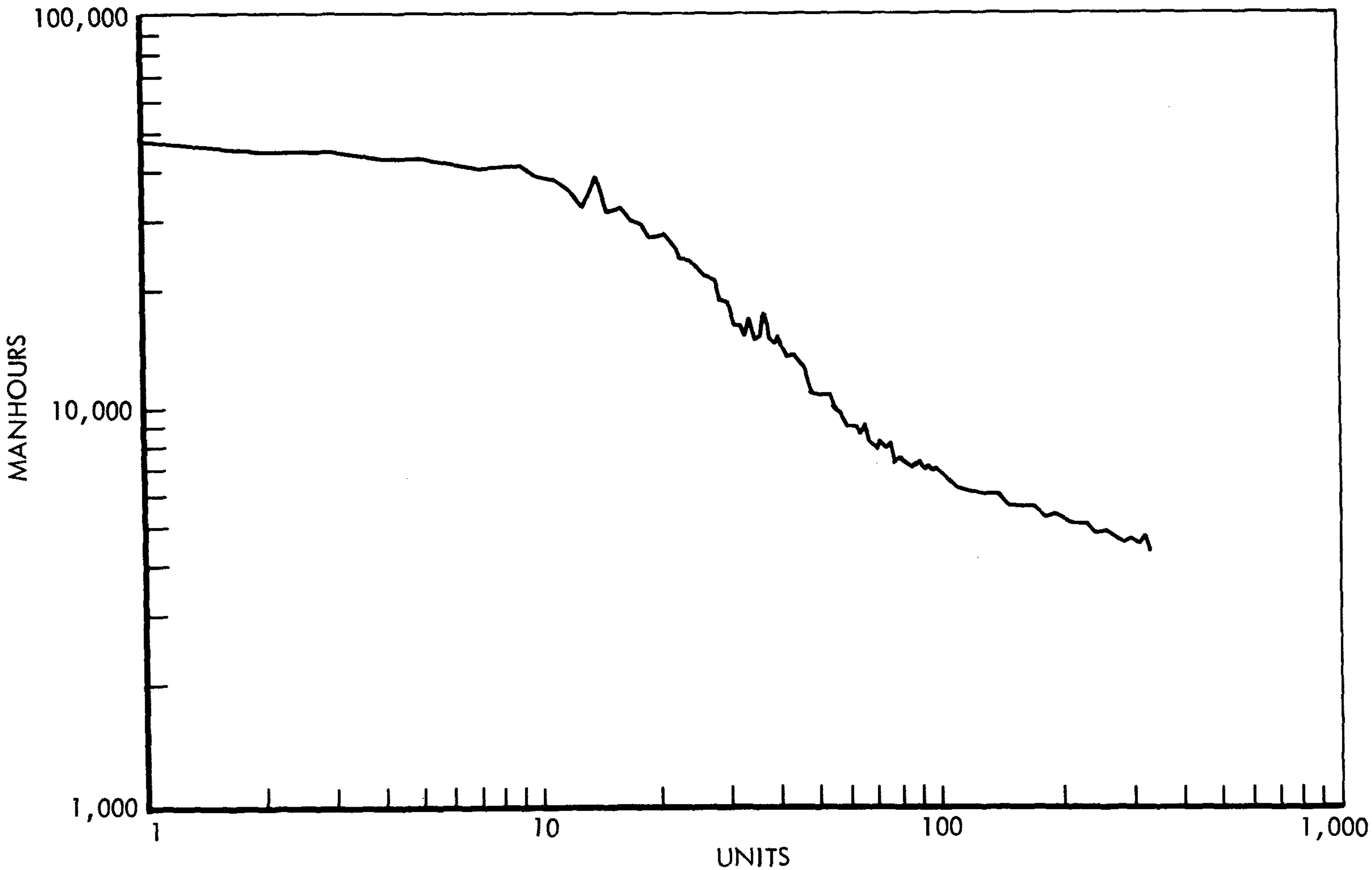


Figure 2.1-4: BOMARC "B" PRODUCTION EXPERIENCE

referred to as "X%" learning curves, where X is the ratio of costs for the 2Nth unit to those for the Nth unit. Thus, these curves can be expressed by

$$C_N/C_1 = N^{1.44 \ln X}$$

where C_N is the cost of the Nth unit, X is the learning curve percentage, and C_1 is the first-unit cost. It can be seen from Figure 2.1-4 that, to match the average cost of hardware units, the effective first-unit cost is different from the actual. "First-unit cost" used in this report is the effective cost.

Experience shows that learning percentages for aerospace hardware range between 85 and 95%, depending on hardware complexity. Unless otherwise indicated, 90% learning has been assumed for studies under this contract.

Historical Cost Trend Parameters

Cost trend parameters should be easily available physical quantities (e.g., weight, volume) and must have a real relationship to costs.

To be usable, the parameters used to define cost trends must be quantities that are functionally related to the technical aspect of design that is the subject of choice. For example, if two different materials are being considered in some design application, estimation will be simplified if cost is related to material type and weight, whereas a cost estimation based on fabrication time will be complex and unworkable on the preliminary design level.

The chosen trend parameters must also possess a logical relationship to cost---a frequently misunderstood point---because parameters that are not logically related can lead to errors in cost estimation. For example, Figure 2.1-5 shows a correlation of launch vehicle stage first unit (less engine subsystem) costs with propellant weight. The cost correlation indicated is good in that data scatter is low, but consideration of the logical relationships shows that the different densities or mixture ratios of various types of storable propellants (N_2O_4/UDMH against RFNA/UDMH, for example) will indicate different stage costs for essentially

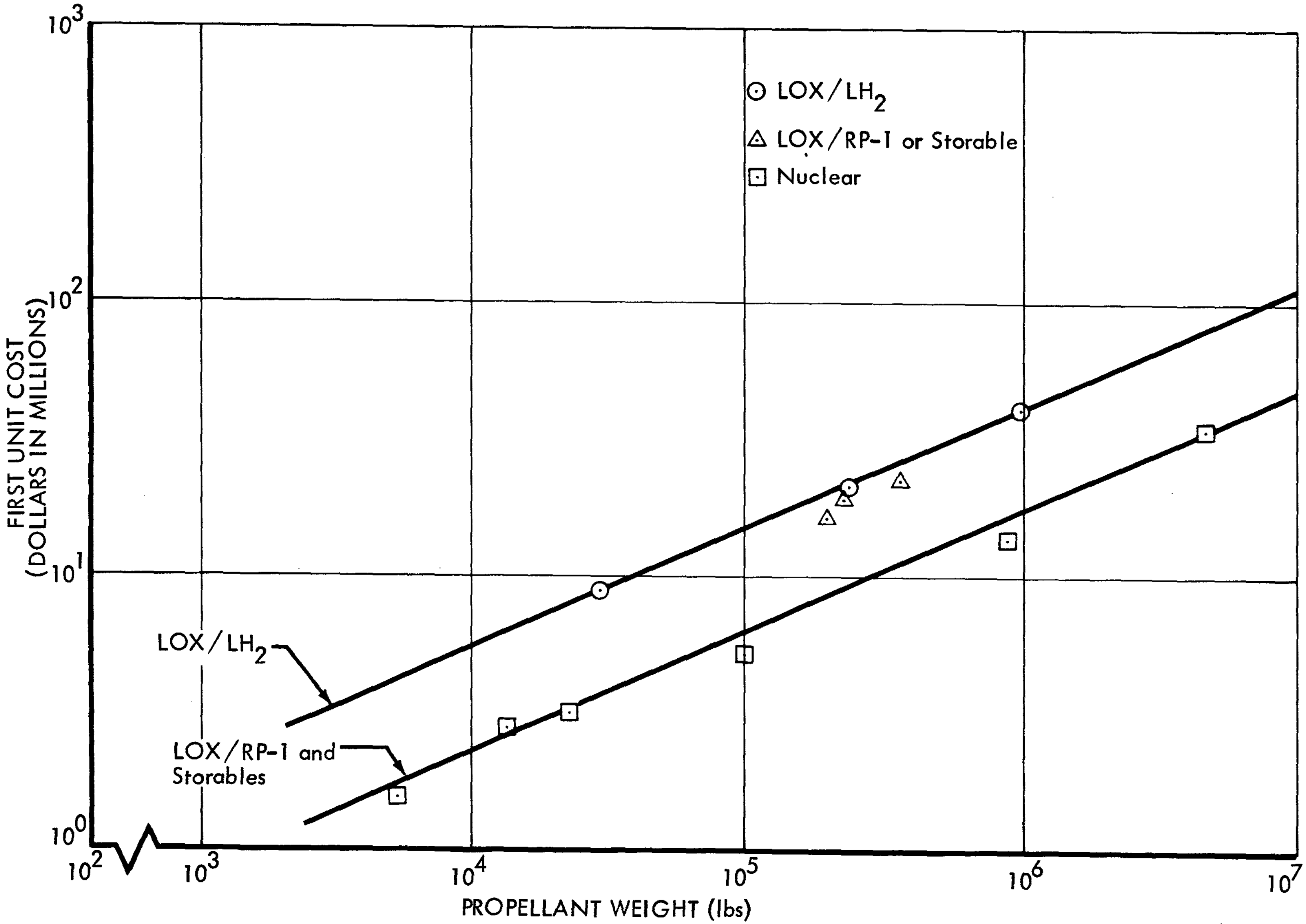


Figure 2.1-5: LAUNCH VEHICLES UNIT #1 COST (Less Engines)

identical hardware. Another example is rocket-engine unit cost with thrust, which ignores the differences between low- and high-pressure engines or between bleed cycle and gas generator drive turbopupms.

Statistical Approach to Trends

The scatter present in all cost data makes it necessary to apply statistical methods of curve fitting to extract the important relationship of cost to the trend parameter being considered.

Serious scatter exists in any collection of cost data. Data scatter itself does not indicate that the trend parameter was poorly chosen; it indicates only that hardware programs are imperfect. This scatter may arise because some programs are beset by problems and suffer cost growths, because retrofits are frequently required, because engineering changes are sometimes introduced, because a carry-over of experience occurs in some programs and not in others, and because weight-reduction programs are sometimes instituted. Thus, a method of extracting the important information from imperfect data must be developed.

Statistical analysis provides a technique for handling data scatter. The application of curve fitting with minimum rms deviation is a smoothing operation that will detect the correlation between cost and the trend parameter selected logically.

In applying this method, experience is used to observe that most cost correlations take the form of simple power laws, i.e., straight-line relationships on log-log plots. Thus, if:

Individual cost value = C_i

Individual correlation parameter value = P_i

the statistical cost expression is given by:

$$C = bP^a$$

where:

$$a = \frac{\overline{C_i P_i} - \overline{C}_i \overline{P}_i}{\overline{P_i^{\,2}} - (\overline{P}_i)^2}$$

$$b = \log^{-1} (\overline{C}_i - a\,\overline{P}_i)$$

where the barred quantities indicate averages taken over all data points considered.

Figure 2.1-6 shows the results of such a curve fitting when applied to correlating rocket-engine first unit costs with engine subsystem weight. Three different curves are fitted by excluding various data points. Also shown is a Pratt & Whitney cost model trend.

System Costs From Fundamental Elements

Better system cost correlation can be accomplished by breaking down a system into its structural, mechanical, and electronic components rather than by subsystem (e.g., communication, power) because of the closer correspondence of costs to such components.

In space systems, a major portion of total costs is assigned to subsystems other than what is commonly referred to as "structure." In these systems, the structure (which corresponds to the airframe in aircraft programs) becomes one of the subsystems. There is a tendency to use the subsystem as the finest subdivision of cost elements in space systems cost predictions, because, by inference, all costs for members of one subsystem class should behave in the same way (i.e., show a common trend). This approach to system costing has produced difficulty in establishing workable cost trends for subsystems other than structure. In many cases (e.g., a guidance and control subsystem), statistical analysis is unable to show a trend within reasonable deviation limits.

The lack of correlation arises because the precept of a logical relationship between cost and correlation parameters has been violated. A typical

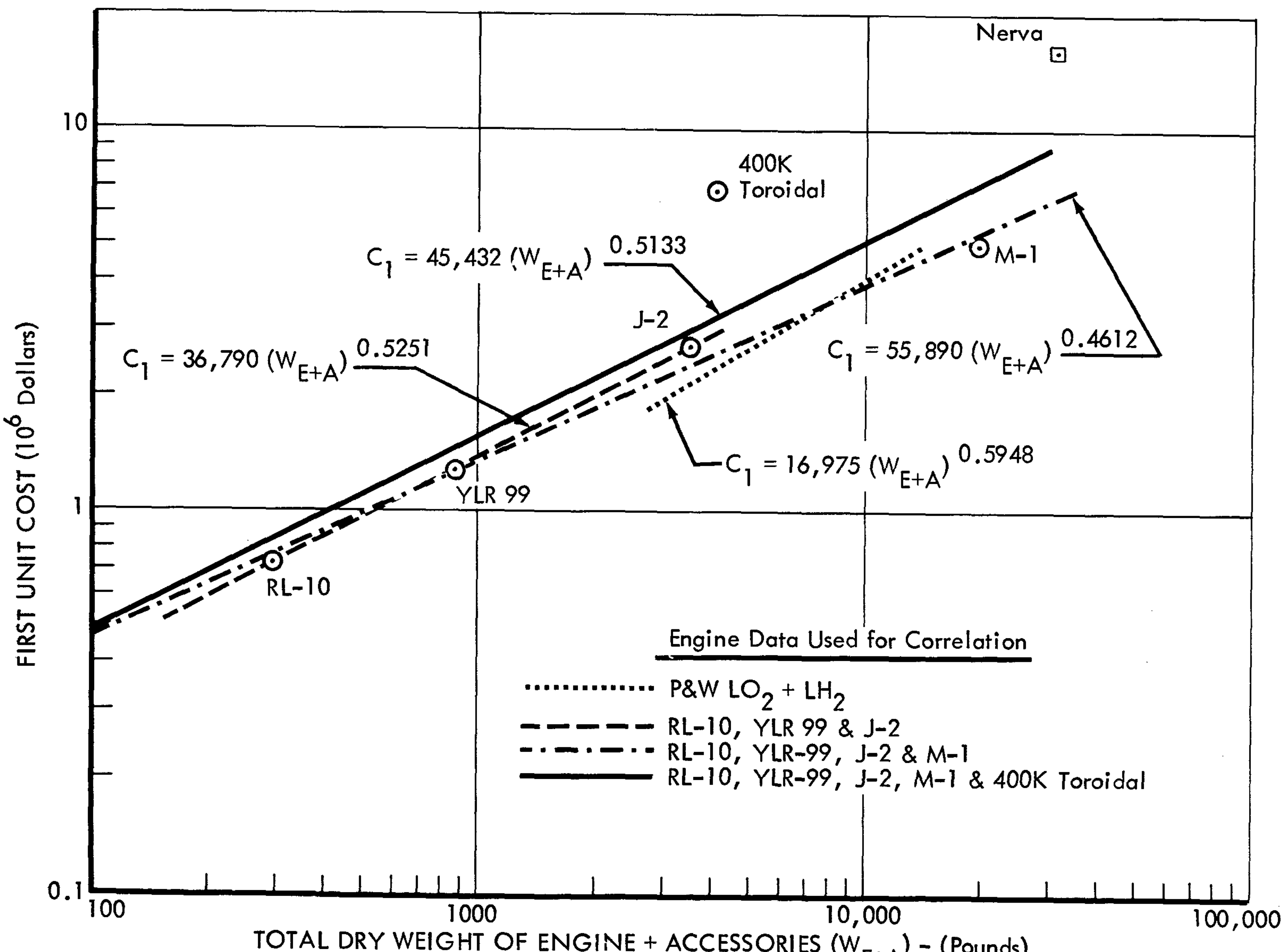


Figure 2.1-6: ROCKET ENGINE RECURRING COSTS - WEIGHT CORRELATION

subsystem comprises three types of hardware in differing quantities: structures, where the hardware functions to transmit load; mechanisms, where the hardware functions to transmit motion; and electronics, where the hardware functions to transmit and condition electrical signals. The important cost relationships for each of these types obviously differ from one to another. In some cases, structures and mechanisms show similar behaviors. The way these hardware types are mixed and the significance of structure in other subsystems is shown in Figure 2.1-7, which tabulates weights for a small unmanned spacecraft system by subsystem and by hardware type. Note that in a total system weight of 418 pounds, the "structural subsystem" comprises 52 pounds, or 12%; but structural components found within all subsystems comprise 286 pounds, or 68%.

The result of fitting an equation of the form:

$$\text{Cost} = b_e \,(\text{electronic component weight})^{a_e} + b_s \,(\text{structural component weight})^{a_s}$$

is shown in Figure 2.1-8. As expected, electronic component unit costs show much less improvement with weight increases than do unit costs for structural components.

Effect of Complexity on Cost Models

The occurrence of cost bands on a structures cost-weight plot is due to the varying hardware complexity as measured by part size.

Previous arguments imply that structure, when isolated from total space systems, should show a single cost trend with weight. This does not occur, as shown by Figure 2.1-9, which plots the first-unit cost for structure against weight for a large number of space systems and components. The data points tend to group into bands by geometric types of hardware, with the bands showing significant cost separations.

SUBSYSTEM	SUBSYSTEM WEIGHT (lb)	ELECTRONICS WEIGHT (lb)	STRUCTURES WEIGHT (lb)
Power	92.07	40.17	51.90
Communications - Package A	39.71	28.52	11.19
Communications - Package B	21.44	18.36	3.08
Attitude Control - Flight Electronics	45.44	24.28	21.16
Attitude Control - Reaction	27.48	0	27.48
Velocity Control - Engine Feed	47.63	0.33	47.30
Velocity Control - Engine	5.00	0	5.00
Structures	79.57	0	79.57
Mechanisms	23.47	0	23.47
Assembly and Integration	36.51	20.61	15.90
TOTAL	418.32	132.27	286.05

Figure 2.1-7: SPACECRAFT SUBSYSTEMS WEIGHTS BREAKDOWN

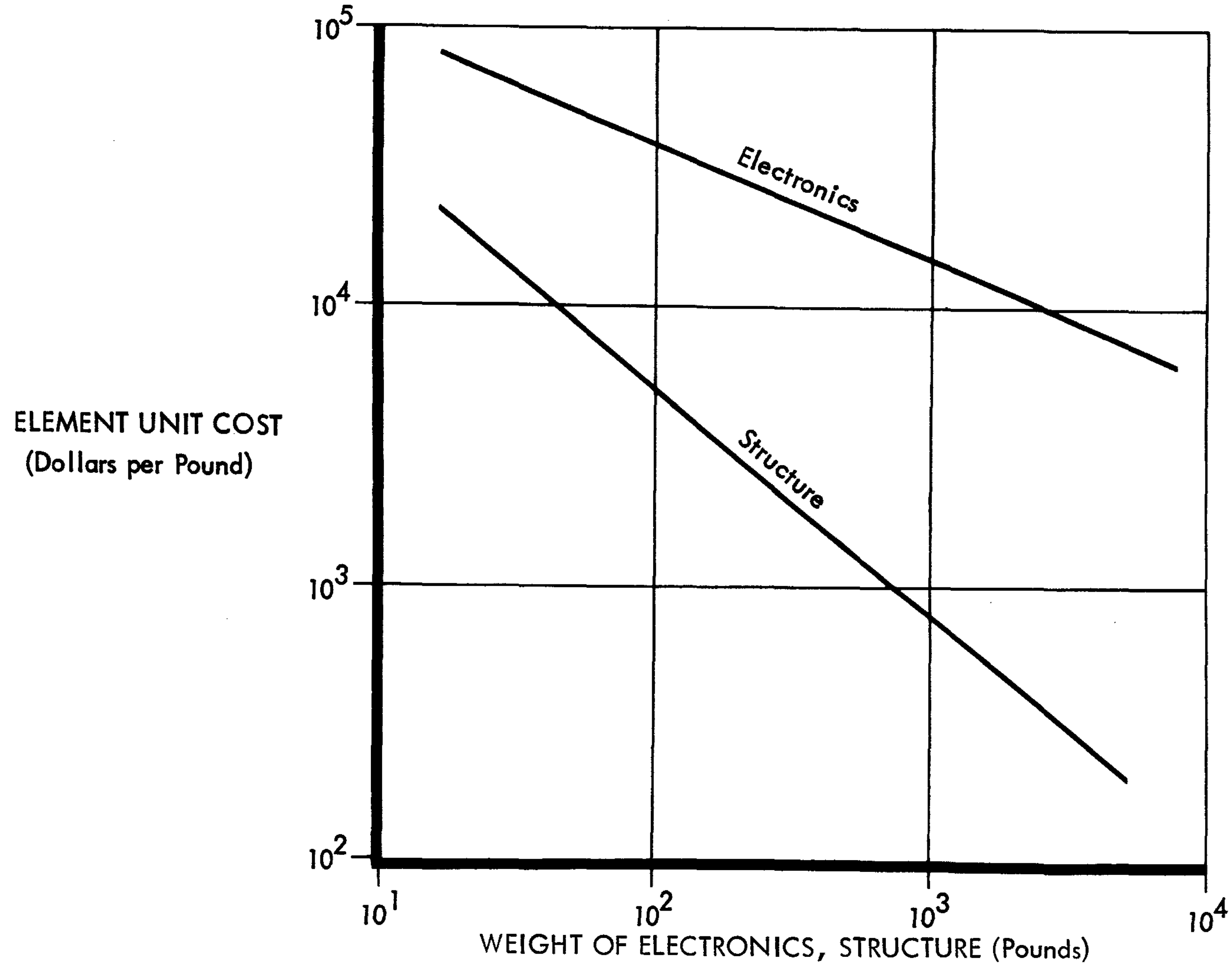


Figure 2.1-8: **SMALL UNMANNED SPACECRAFT COST DATA**

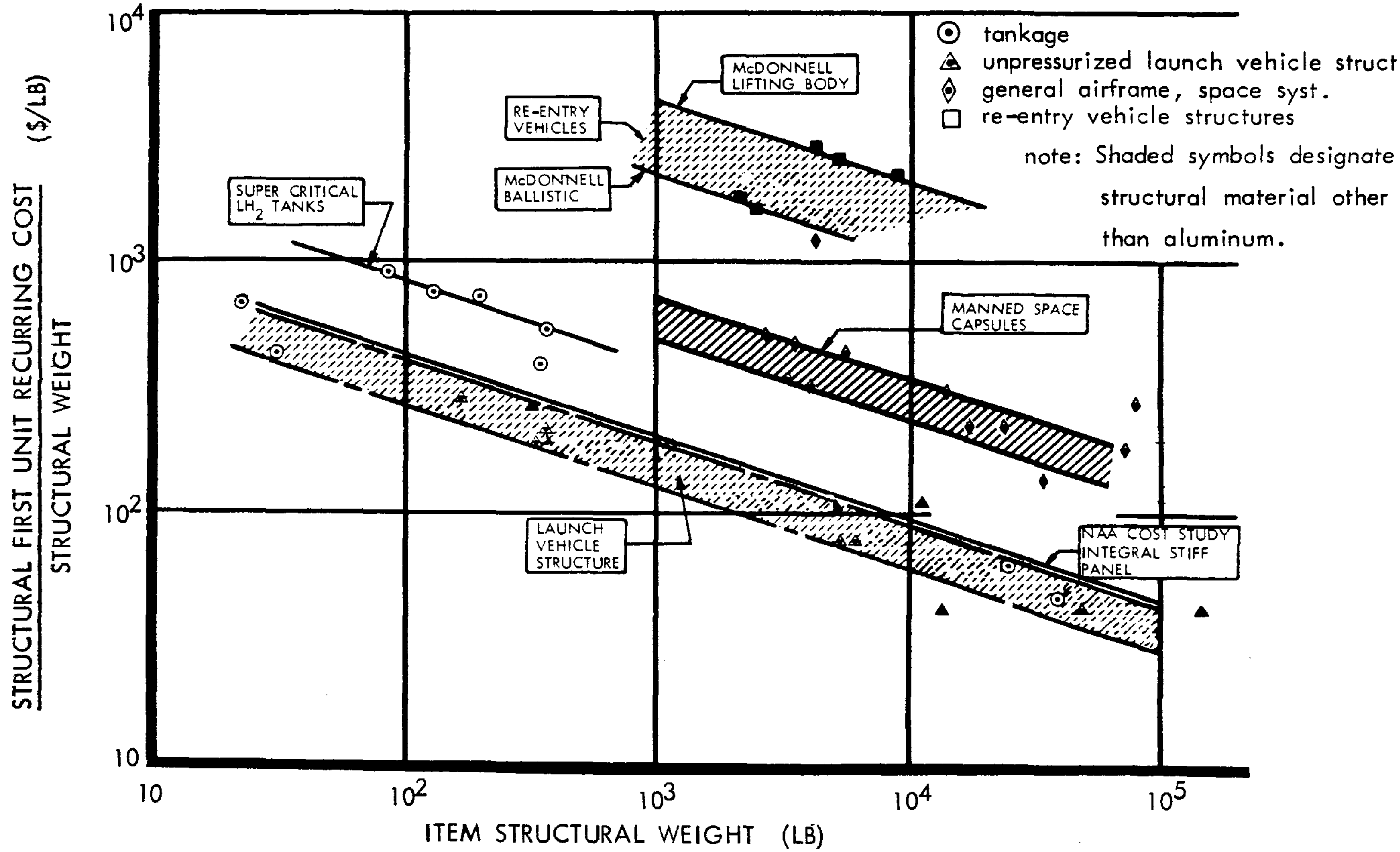


Figure 2.1-9: EFFECT OF COMPLEXITY ON COST

If a single structural component is examined, with geometric similarity maintained throughout a range of sizes and weights (e.g., LH_2 supercritical storage tanks), a discrete trend is noted. This trend indicates that unit cost decreases as part size increases. The next topic shows that geometric relationships explain this trend.

It can be seen that if a structure were built up of many such small components, the unit cost would be higher than if a similar structure with the same total weight were built up of a few large components. This accounts for the indicated high cost of entry vehicles, which are made up of many small parts.

More study is required to demonstrate analytically the effects of complexity on cost.

Significant Trends

There are similarities of cost trends for diverse geometric types of structure that can be logically identified with part area.

The cost bands on Figure 2.1-9 have similar trends (slopes) that cannot be ascribed to coincidence. Statistical curve fitting shows slopes that are nearly the same for entry vehicles, manned space capsules, tankage, and launch vehicle costs. Moreover, a trend taken from independent study, the NAA data (Reference 1), shows the same slope.

The slope of these bands is numerically close to 1/3. Thus, if cost per unit weight is:

$$C/W \sim W^{-1/3}$$

then

$$C \sim W^{2/3}$$

which, if $W = \rho V$, where V = volume, gives:

$$C \sim V^{2/3}$$

but

$$V^{2/3} \sim \text{area}$$

so that cost is proportional to area.

It is easily understood how cost could be related directly to part area, since most manufacturing operations are concerned with working on the surface of parts or creating new surfaces.

Electronic packages, packed to a given density, have approximately the same number of parts per pound regardless of package size. Thus, electronics should have costs that show little improvement with increasing size.

2.2 TRANSPORTATION COSTS

Significance of Transportation Costs

The concept of transportation cost is used in cost trades on aerospace hardware to discriminate between heavyweight and lightweight design alternatives, and can represent a value comparable to, or higher than, that of the hardware itself.

Transportation cost is the system cost element associated with transporting mass from one condition of location and velocity to another; such cost is usually expressed in dollars per pound. It is a frequently used concept in aerospace economics and has been applied to commercial aircraft for many years. Its basic applications are (1) a shorthand method of including the costs of launch vehicle hardware in system-costing exercises, and (2) a means of evaluating the economic merits of lightweight and heavyweight design alternatives.

The first application actually involves a definition of the term "transportation cost" that differs from the second application. The second application is extremely important in aerospace economics; a clear understanding of the differences between the two applications and of the numerical differences of the two types of transportation costs involved is vital to performing correct economic trades and to understanding the uses described in the remainder of this document.

Figure 2.2-1 shows marginal transportation costs for a typical planetary mission as a function of total velocity change. Note the high cost levels and rapid cost increases at higher velocities. These costs are significantly higher than most hardware recurring costs.

Difference Between Total and Marginal Transportation Costs

The true measure of weight utility is marginal transportation cost (as given by the change in launch system cost per unit change in payload weight), not total transportation cost (that is, launch system cost divided by payload weight).

In the first application mentioned previously (the shorthand method), it is desirable that total launch system cost be obtainable by multiplying some unit cost (\$/lb) by payload weight. Obviously a unit cost obtained by reversing the multiplication with a known launch system cost and payload weight will be applicable. This quantity will be referred to in the balance of this document as "total transportation cost."

This quantity does not measure the economic utility of weight reduction, and is incorrect when used in the second application.

In comparing cost-weight candidates, the cost that should be applied is the change in launch vehicle cost as the payload weight varies a small amount from some base point. This is true because the value of a payload weight reduction must be repaid by a dollar savings in the launch system. The transportation cost defined in this fashion will, in future references, be called the "marginal transportation cost."

Total and marginal transportation costs are not equivalent (Figure 2.2-2). The upper plot in the figure depicts the total cost per launch assignable to a low Earth orbit launch system for a range of design payloads. This curve is a real cost prediction for future systems; it shows that total transportation cost, $Cost/W_{PL}$, will always be larger than marginal transportation cost, $d(Cost)/d(W_{PL})$. Actual values for these two quantities

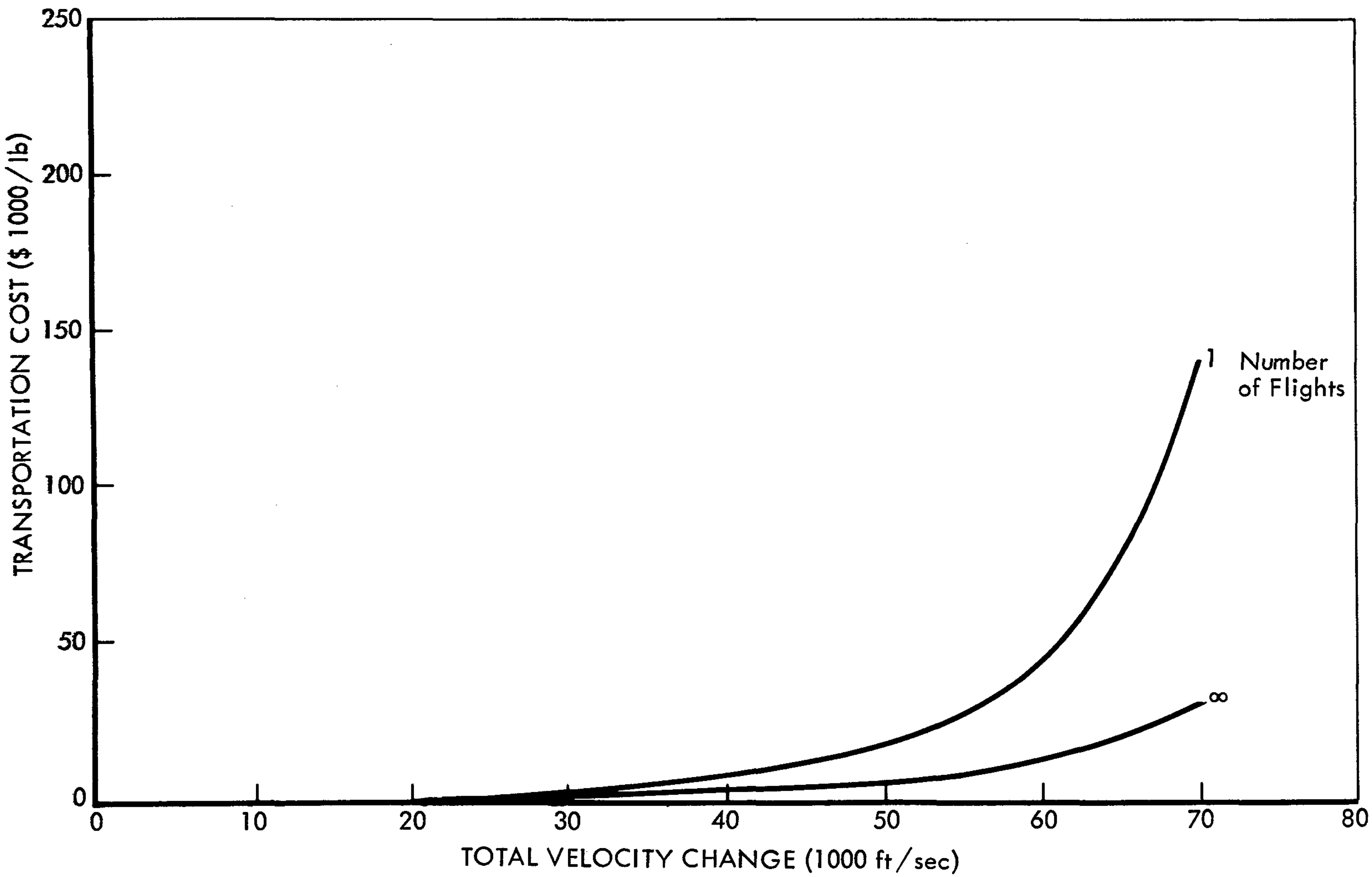


Figure 2.2-1: MARS LANDER MISSION TRANSPORTATION COST NUCLEAR (Modularized Stages)

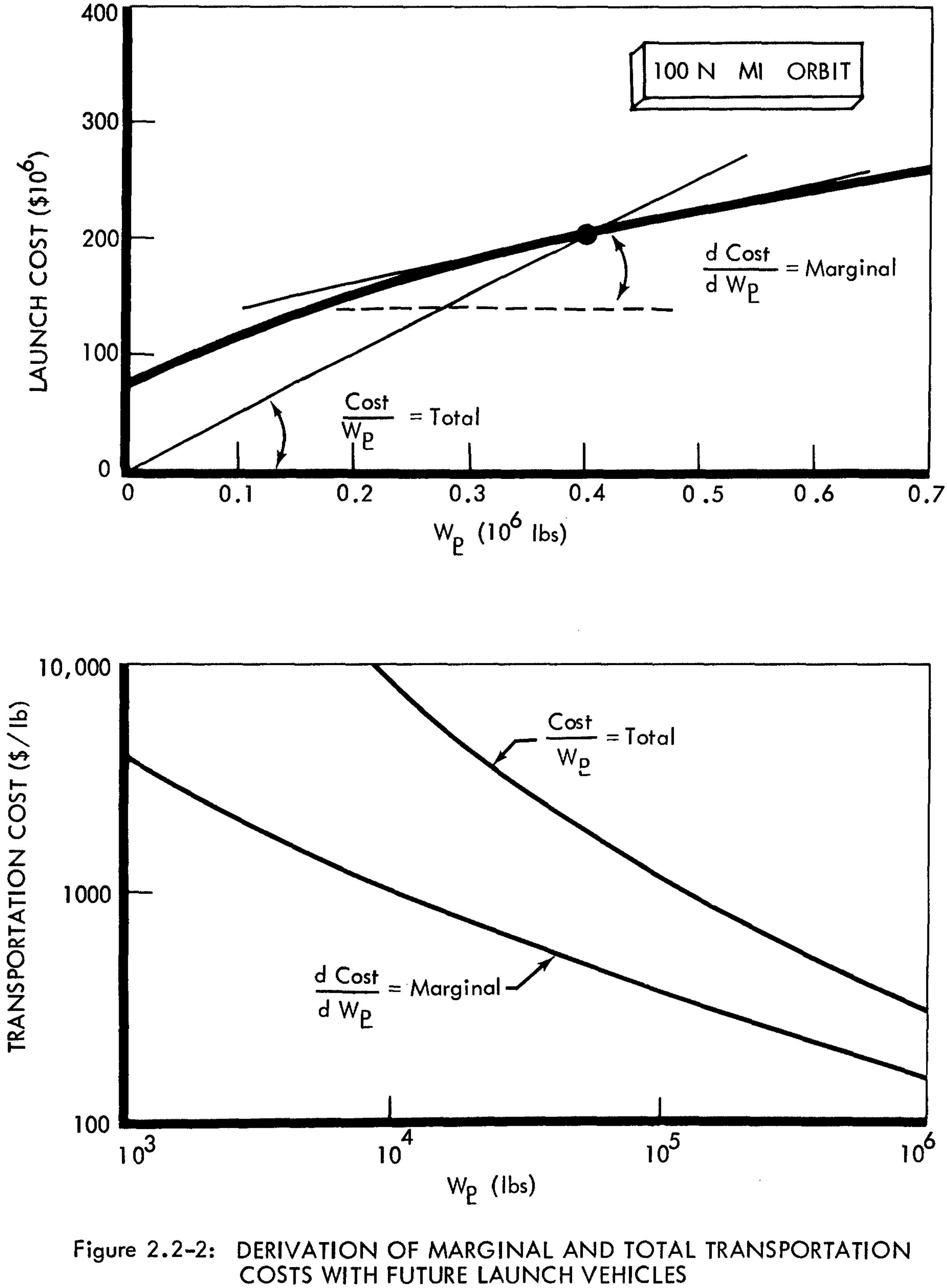


Figure 2.2-2: DERIVATION OF MARGINAL AND TOTAL TRANSPORTATION COSTS WITH FUTURE LAUNCH VEHICLES

are shown in the lower plot. Note that both costs decrease as W_{P_E} increases.

Establishing Marginal Transportation Cost on Future Launch Vehicles

To compute marginal transportation cost, it is necessary to understand how costs of all launch system elements change with payload.

Many cost elements make up a new launch system (e.g., hardware development, manufacturing facilities, test facilities, launch operations). Any element that is affected by payload size contributes to marginal transportation cost. These elements, and their cost trend expression derived from historical data, are listed in Figure 2.2-3. These expressions, with the assumption of a 30-flight program, were used to construct Figure 2.2-2.

Only by establishing such a cost model can marginal transportation costs be computed for a new launch system, because only by including all cost elements can the true system impact of payload weight changes be evaluated.

It is important to note, however, that if the launch system is not being sized specifically for the payload design being considered (e.g., a "workhorse" booster is postulated), then the launch system cost change due to payload weight variations is undefined. This common situation does not preclude the application of the marginal transportation concept. In this case, the payload is economically matched with the existing booster by a method described in Section 2.4.

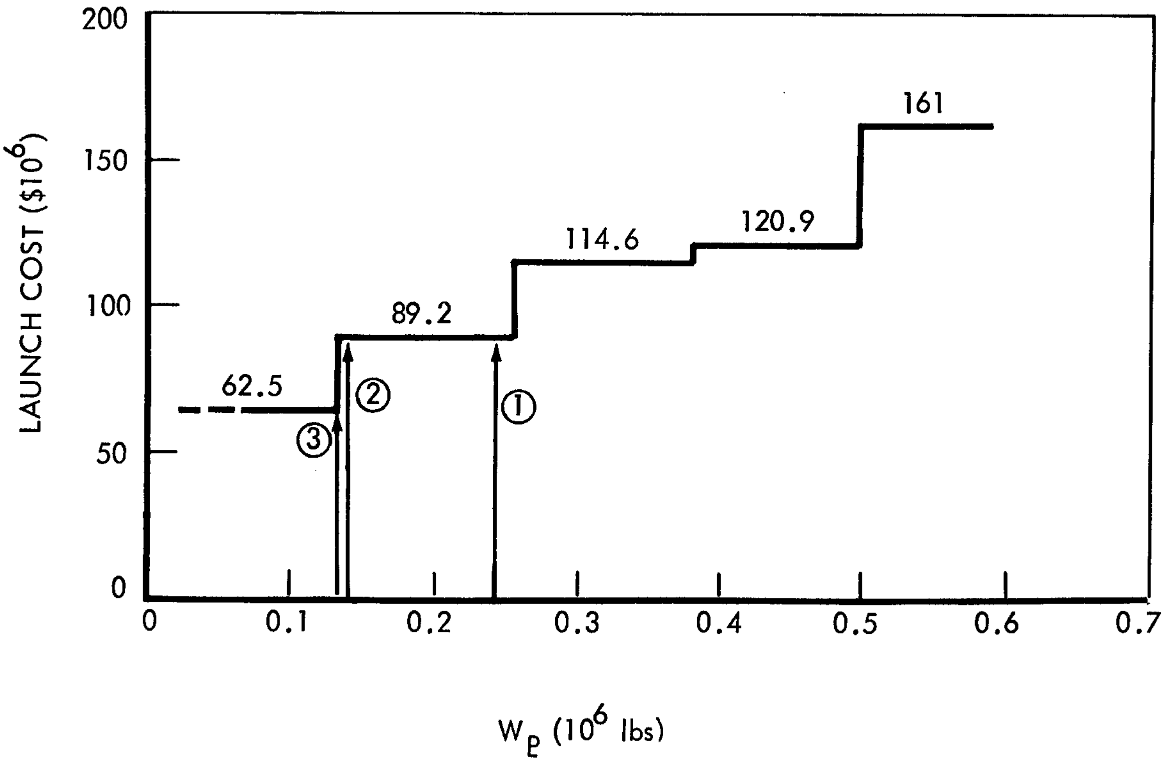
Marginal Transportation Costs of Payload on Existing Launch Vehicles

No value of marginal transportation cost can be defined for an existing launch vehicle (except in programs involving multiple launches for a single payload); for such a vehicle, a unit change in payload weight produces no real change in launch system cost.

Figure 2.2-4 shows typical launch vehicle cost variation with payload weight for a family of improved and intermediate Saturn vehicles (Reference 2). The costs shown are the sum of the average hardware cost for

COST ELEMENT	COST EXPRESSION
First Stage (LOX/RP-1) R&D	$2.984 \times 10^7 \, W_P^{0.244}$
Second Stage (LOX/LH_2) R&D	$2.480 \times 10^7 \, W_P^{0.244}$
First Stage Engines R&D	$4.114 \times 10^5 \, W_P^{0.557}$
Second Stage Engines R&D	$6.397 \times 10^5 \, W_P^{0.557}$
First Stage Hot Run Test Facility	$4.923 \times 10^7 + 25.58 \, W_P$
Manufacturing Facilities	$1.302 \times 10^8 + 28.65 \, W_P \;\; N/T$
Launch Complex	$3.00 \times 10^8 + 432.4 \, W_P$
First Stage #1 Unit	$3.178 \times 10^3 \, W_P^{0.729}$
Second Stage #1 Unit	$6.592 \times 10^2 \, W_P^{0.809}$
First Stage Engine #1 Unit	$1.089 \times 10^4 \, W_P^{0.461}$
Second Stage Engine #1 Unit	$1.111 \times 10^4 \, W_P^{0.461}$
Integration & Management	1.92×10^7
Recurring GSE	10% of Hardware
Launch Operations	$2.282 \times 10^7 + 2.684 \, W_P$
*Staging Velocity = 14,000 fps Learning Curve = 90%	N/T = Annual Production Rate

Figure 2.2-3: LAUNCH VEHICLE* COST ELEMENTS FOR VARIABLE PAYLOAD



	Case ①	Case ②	Case ③
W_P	= 240,000#	140,000#	130,000#
Launch Cost	= $89,200,000	$89,200,000	$62,500,000

	Cases ① and ②	Cases ② and ③
Δ W_P	= 100,000#	10,000#
Δ Launch Cost	= $0	$26,700,000

Figure 2.2-4: DERIVATION OF MARGINAL TRANSPORTATION COSTS FOR EXISTING LAUNCH VEHICLES

30 units (after the first 15) plus recurring flight costs for ground support equipment and facilities and for integration and management.

The discontinuous nature of the cost variation makes marginal transportation cost undefined because, as the examples show, a unit change in payload weight can produce no change, infinite change, or any intermediate value of launch system cost variation. Any attempt to apply the marginal transportation cost concept to such a problem will produce no valid economic information. However, a program such as a manned planetary mission can involve multiple launches with orbit rendezvous to place a set of mission hardware in space. In this case, payload (i.e., mission hardware) will determine the number of launch vehicles required. If payload weight variations are sizable, the number of launch vehicles may change by one or more.

For example, if a Mars vehicle weighs 3,000,000 pounds in Earth orbit, 12 Saturn V launches would be required. A weight trade involving 8% of this 3,000,000 pounds would change the number of Saturn V's by one, with corresponding launch system cost change. Such changes, on the average, could be priced by using the total transportation cost of Saturn V (approximately $500/lb), which becomes equal to the marginal transportation cost for this example. However, in such cases, it is most accurate to consider only the total launch system cost change and treat each case as unique.

The problem of matching new payload design to an existing launch vehicle is discussed in Section 2.4.

Marginal Transportation Costs of Launch Vehicle Hardware

To a first approximation, the marginal transportation cost for launch vehicle stages is defined by costs of previously expended stages, and is effectively zero for a first stage.

The marginal transportation cost concept is useful in design trades for launch vehicles as well as payloads if it can be properly evaluated. The proper criterion is unchanged: the change in launch system cost for a unit weight change. Its application to launch vehicles is complicated by the "multiplier" effect---the cascading of inert weight changes through the weights of propellant, associated propellant containment, propulsion, and so on.

Performance trades (Reference 3) show that, for first stages and single-stage-to-orbit launch vehicles, the multiplier effect is not strong, being on the order of 6% for LOX/LH_2 unstaged vehicles. Since all cost data have a wider tolerance than 6%, this effect can safely be ignored for these vehicles.

Upper stages, in contrast, have high exchange ratios with lower stages, and the multiplier effect becomes quite significant. Coupling a performance analysis with cost trend data (Figure 2.2-3) will produce the means to compute marginal transportation costs for these stages.

2.3 CONCEPT SELECTION TECHNIQUE

Need for an Economic Method to Screen Concepts

If a program is to be ultimately cost effective, cost must be used as a screening tool in the earliest program phases.

Making choices between alternates on a cost basis is not as familiar a process as making choices on other bases. Most aerospace engineers are conditioned to searching out alternates that maximize performance and minimize weight. Often, the goal appears to be the promotion of new technology for the sake of its newness.

The "cost" of items is often treated as quite mysterious and not amenable to any reasonable analysis. It is *not* easy to perform totally adequate cost analysis, especially long before the fact; but for a proper evaluation of any program, cost must be the decision tool used from the start, because as each program decision is made, there is correspondingly less latitude for making the system cost effective. For example, there may be a question of whether a booster tank wall should be stiffened by tee or by waffle-pattern stiffeners. A manufacturing trade may show a sizable cost difference, but a much more important cost element became part of the program when the booster propellants were picked and when the staging velocity was set. Frequently, these major decisions are made on the basis of maximizing performance.

Figure 2.3-1 illustrates the numerous possible alternate mission modes for a Mars lander mission. Two goals have to be satisfied. First, it is desirable to screen concepts so that a manageable number of total mission modes can be compared. Second, the screening process should retain those mission modes having least cost. An economic technique has been developed to accomplish this screening. The technique illustrated starts at the top of a vehicle stack (in this case, the Earth reentry vehicle) and works down sorting out the most promising stage concepts and using them for assessment of the elements below.

Establishing Performance and Cost Data

To permit economic screening, it is necessary to establish performance and cost data.

Parametric weight and cost estimating methods are the basic tools required for the concept selection technique. The accuracy of the concept selection is obviously the accuracy of these basic tools. Once again, there is a need for good cost data.

To illustrate: The concept selection technique will be applied to Earth entry vehicle alternates. Figure 2.3-2 tabulates the weight data used for the three candidate entry vehicle concepts. Concept A assumed the use of two standard Apollo command modules (CM's) to return the six-man crew. The retrorocket weight required to slow the CM's to their current entry velocity capability is also shown. Concept B assumed two modified Apollo CM's, where the modification would be in the guidance and thermal protection systems. Concept C assumed the development of a new six-man vehicle suited to the Mars return entry conditions.

The cost data must contain comparable estimates of nonrecurring, recurring, and marginal transportation costs. Figure 2.3-2 shows such data

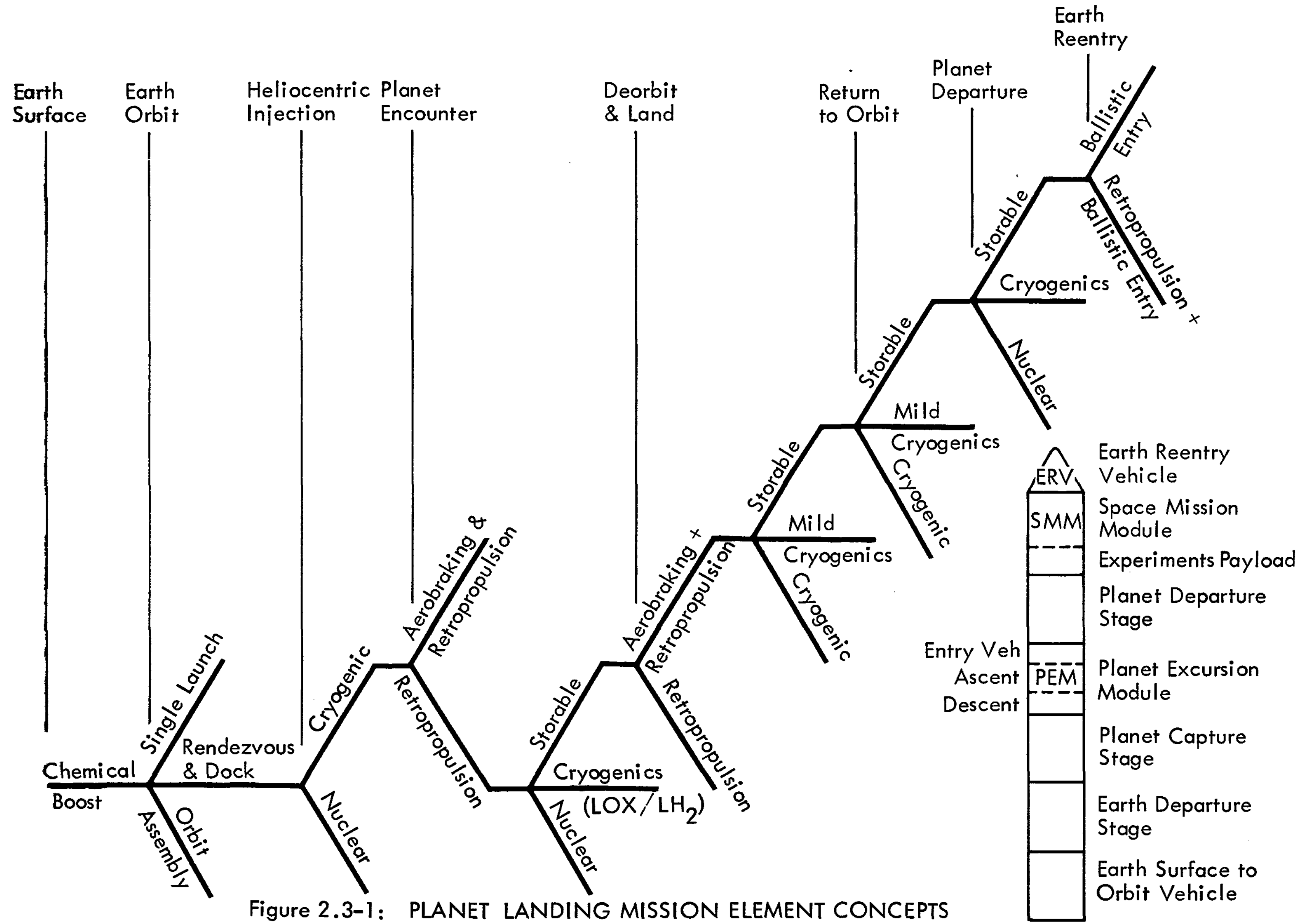


Figure 2.3-1: PLANET LANDING MISSION ELEMENT CONCEPTS

WEIGHT - THOUSANDS OF POUNDS				COST - BILLIONS OF DOLLARS			
Reentry Vehicle Description	Reentry Vehicle	Retro Provisions	Total R/V + Retro	Total Vehicle R&D	Vehicle Rec Hrdw Cost/Flt	Transportation Cost per Flight @$12,000(1) per Lb	Transportation Cost per Flight @$6,200(2) per Lb
Two Apollos + Retro (A)	21	39	60	0.2	0.1	0.72	0.372
Two Apollos (Mod Guidance & Therm) (B)	21	0	21	0.4	0.1	0.252	0.13
New Six-Man Reentry Vehicle (C)	10.5	0	10.5	2.0	0.1	0.126	0.065

(1) - Propulsion Braking @ Mars

(2) - Aero Braking @ Mars

Figure 2.3-2: EARTH REENTRY VEHICLE COMPARISON DATA

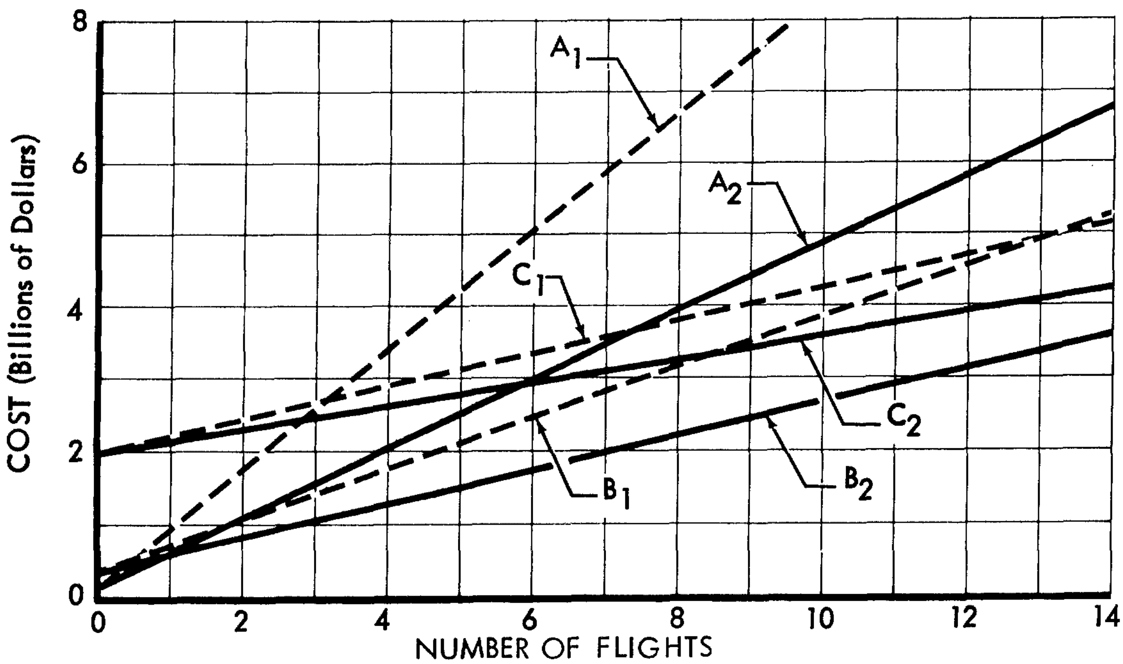


Figure 2.3-3: EARTH REENTRY VEHICLE CONCEPT SELECTION

for the three entry vehicle concepts. Two early estimates of marginal transportation cost are shown corresponding to chemical propulsion braking and aerobraking at Mars.

Analyze Data and Select Concepts for More Detailed Study

Candidate systems for more detailed costing studies can be identified from a plot of total cost versus number of flights.

The cost data shown in Figure 2.3-2 represent that part of the total system cost of a Mars lander mission attributable to the Earth entry vehicles. The primary purpose of such a presentation is to show the relationship of R&D costs (cost axis intercept) and recurring costs (slope of the lines). Note that the predominant recurring cost for this element is due to transportation.

The general conclusion that can be drawn from the data shown in Figure 2.3-3 is that two modified Apollo entry vehicles should be used for subsequent evaluations because they are considerably more cost effective for the flight number range expected.

Other applications of the concept selection technique have pointed to no marked superiority between several candidates. In such cases, a decision has to be made on which candidates to carry forward; but at least the display of cost data has been made, which justifies further consideration. It is felt that the procedure just outlined is better than proceeding on the basis of intuition or application of a performance criterion.

2.4 SYSTEM/SUBSYSTEM COST OPTIMIZATION TECHNIQUE (SCOT)

The Cost-Weight Equation---Three Problems

The achievement of economies in aerospace programs depends heavily on establishing the proper balance (Figure 2.4-1) between costs and weights for design candidates at the part, subsystem, and system levels, and can be accomplished by use of the cost margin concept.

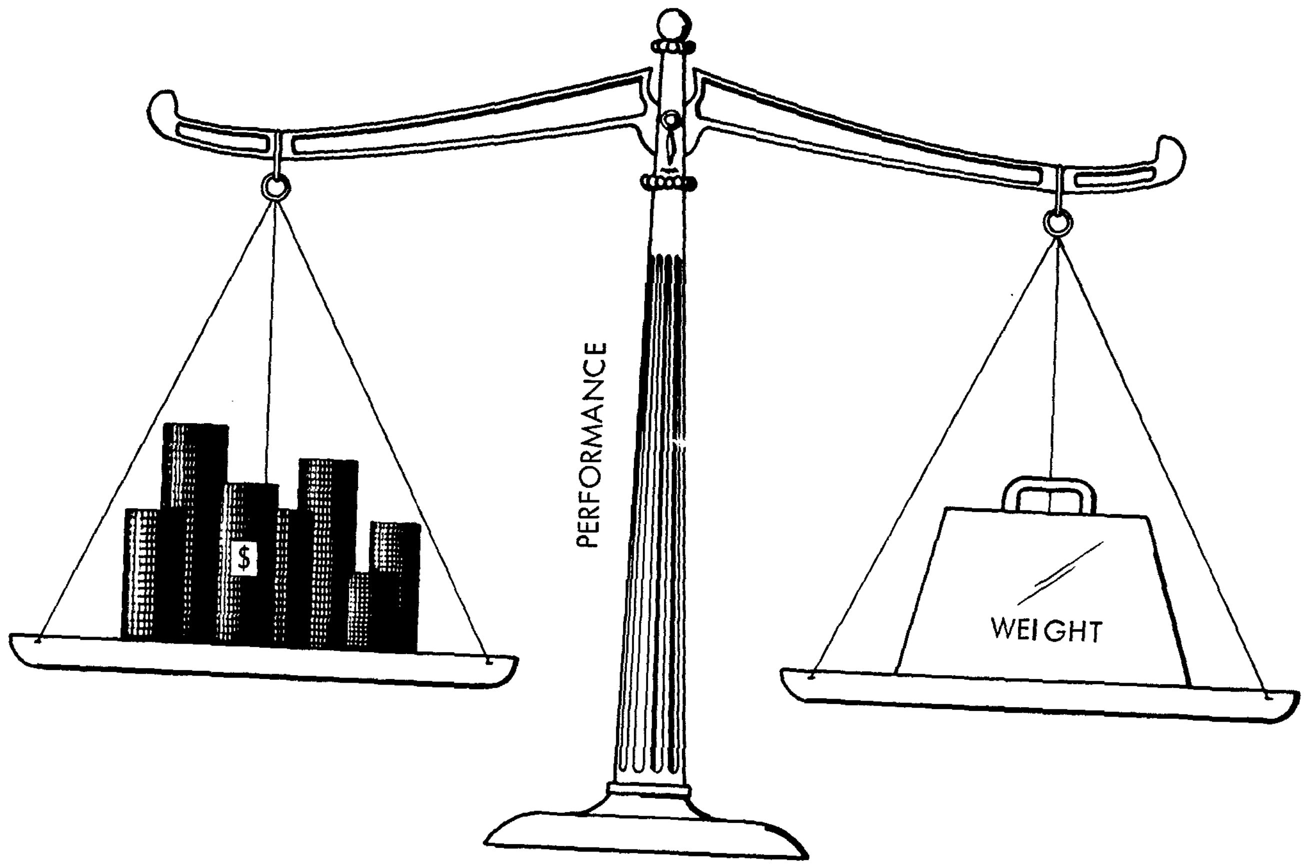


Figure 2.4-1: SOLVING THE COST-WEIGHT EQUATION

A major difficulty in cost-effective design is to determine the proper level of sophistication that should be established as a design goal. Design sophistication can be expensive in dollars, flexibility, and reliability. The aerospace planner needs to know, in advance of hardware program initiation, that the decisions he makes are cost effective. When viewed in the total system context, cost-weight considerations in spacecraft design can present the designer with three types of problems.

Problem 1---The design of new spacecraft to be used with a new booster where subsystem weights being traded are too small to affect booster performance or when cargo weight can be traded for spacecraft weight. Such a system is typified by an orbital entry vehicle for a logistic system in the 1980's.

Problem 2---The design of new spacecraft to be used with a specified booster having definite weight limitations and using existing or new subsystems (e.g., Voyager).

Problem 3---Design of new spacecraft using existing or new subsystems for which a booster may be chosen from a number of alternates. Communication satellites are examples.

A technique growing out of the marginal utility concept of economics has been developed at Boeing---the system/subsystem cost optimization technique (SCOT). It provides an engineering approach to solving all three problems.

Establishing Economic Alternatives

To permit economic choice, it is necessary to establish cost-weight data for candidates having the same function and reliability.

The basis of SCOT is a set of cost-weight plots showing the trend of design alternate costs with varying weight. It is important that only weight be traded for cost. Each candidate part, subsystem, or system must have a common function, equal reliability, and equal life.

The cost plotted for each candidate is total cost and must include development, recurring, and operations costs. Furthermore, the cost for any subsystem must include the cost of integrating that subsystem into the system so that total system costs can be found by summing subsystem costs.

When design candidates are arranged to arrive at a decision in a particular subsystem area, it is necessary to add incremental costs and weights that appear in other subsystems because of a particular design solution.

Figure 2.4-2 depicts a set of candidate subsystems on a cost-weight plot. The points plotted are discrete design solutions. It is also possible to have a continuous relationship between cost and weight of a candidate part or subsystem. An example is a pressure vessel where a material is chosen and design sophistication is varied. A heavy, but low cost, design might use the as-welded properties of the material. Cost would be added, and weight removed, by also considering a design that left weld lands but machined-out material where possible, to take advantage of the base metal properties. The backup document presents such an example (Section 3.4).

Choosing Optimum Alternatives by Balancing Cost Margins

The best cost-weight design candidate is identified by equating the marginal cost of making candidate weight reductions with the marginal transportation cost---accomplished graphically by the SCOT method.

It has been recognized (Reference 4) that the use of a cost-weight merit function, equivalent in space systems to marginal transportation (boost) cost in \$/lb, when applied to a cost-weight plot, such as Figure 2.4-3, identifies the most cost-effective subsystem candidate for that boost cost. Stated in economic terms, this is the process of equating the marginal cost of weight removal to the marginal cost of boosting weight. In Figure 2.4-3, a boost cost of \$300/lb is shown, with Candidate E being chosen. If boost cost were to increase smoothly, Candidate C would be chosen next, with Candidate A chosen last. Similarly, if boost cost were to decrease, Candidates F and G would be chosen sequentially. In no case would Candidates B and D be chosen.

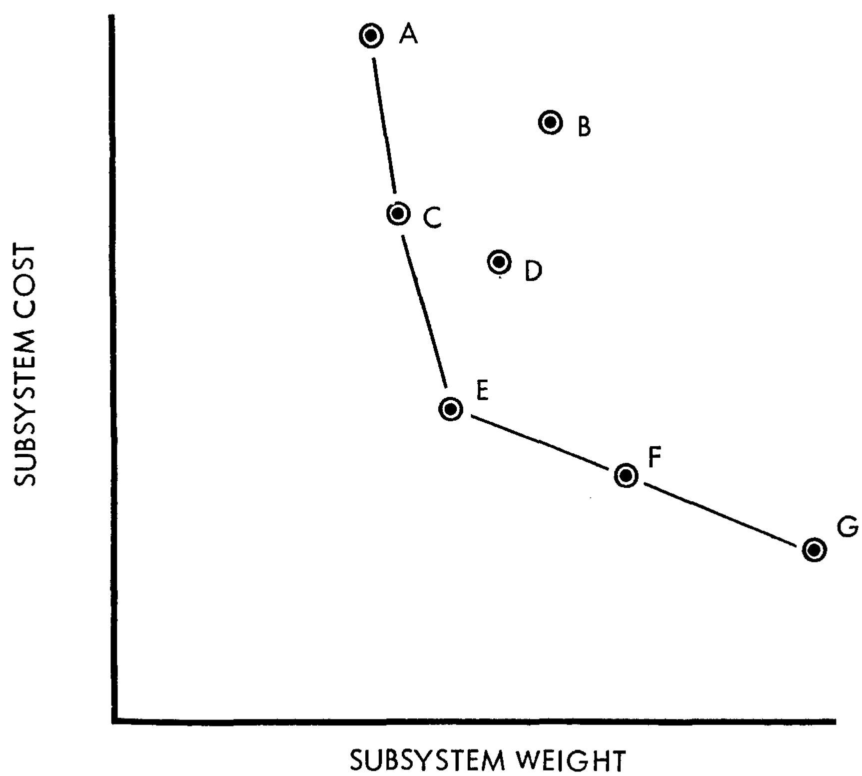


Figure 2.4-2: SUBSYSTEM COST - WEIGHT CANDIDATES
(Fixed Function, Reliability, Life)

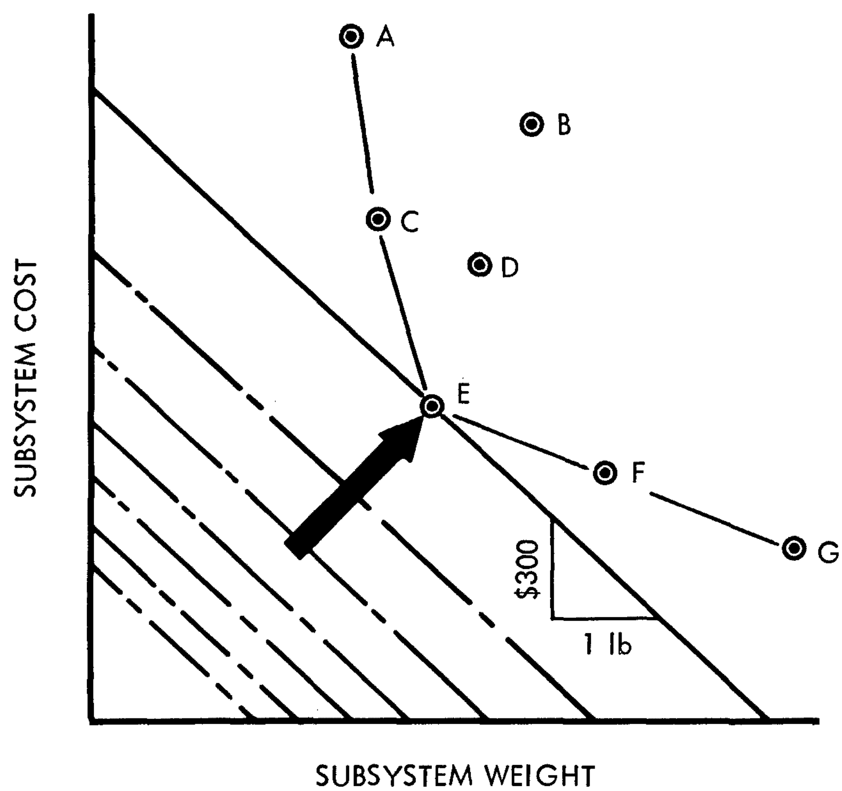


Figure 2.4-3: BALANCING ECONOMIC MARGINS

By performing this operation with boost cost as a free variable, the optimum subsystem can be chosen commensurate with the desired system objective. Problem 1 is solved directly by applying this technique to sets of subsystem candidates and by using the marginal transportation cost of a booster as derived in Figure 2.2-2.

Distributing Weights Within a Fixed Weight Vehicle

By considering marginal cost as a free variable, the SCOT method can be used to balance costs and weights at the subsystem level within a fixed-weight system.

The second problem posed in this section was the cost effective design of a new spacecraft having a specified total weight. Problem 2 is essentially one of distributing weights among subsystems so that total cost is minimized and a specified total weight is realized. To accomplish this end, marginal cost is varied smoothly from low to high values with note taken of those marginal costs at which subsystem weight changes occur. The resultant relationship of weight to marginal cost is plotted. This curve is then entered at the booster payload limit, and an effective cost margin is determined. This marginal cost can then be used to synthesize a system having minimum cost and optimum weight allocation at the specified payload limit.

For example, the initial configuration of a spacecraft using off-the-shelf subsystems shows it to be 20% overweight on a booster with a 585-pound payload capability. Subcontractors are requested to estimate costs if subsystem weights are to be reduced by 20 and 40%. The cost and weight data then established are shown in the table below. The columns labeled "marginal cost" are the costs of making subsystem weight reductions and are generated by dividing subsystem cost increases by the corresponding weight reductions.

Subsystem	Subsystem Weight (lb)			Subsystem Costs ($10^6/unit)			Marginal Cost ($/lb)	
		Reduction			Reduction		Reduction	
	Baseline	20%	40%	Baseline	20%	40%	20%	40%
Mission Equipment	210	168	126	2.20	3.00	7.40	19,000	104,800
Power	112	90	68	1.64	2.10	3.74	20,900	74,500
Communication	100	80	60	0.96	2.24	4.16	64,000	96,000
Attitude Control	70	56	42	2.82	4.40	9.00	112,900	328,600
Propulsion	75	60	45	0.90	1.16	1.62	17,300	30,700
Structure	167	133	100	0.56	0.68	0.84	3,500	4,800
Total System	734	587	441	9.08	13.58	26.76		

A 20% weight reduction across the subsystems produces a system that meets booster payload weight limitations with a cost of $13.58 x 10^6$ per spacecraft. Application of SCOT begins with a set of cost-weight plots for subsystem candidates (Figure 2.4-4). Next, subsystem selection is made for marginal costs from $3500/lb to $330,000/lb. The resulting plot of system weight as a function of marginal cost is shown in Figure 2.4-5. Entering this curve with a 585-lb payload limit identifies an effective cost margin of $30,660/lb. Thus, any weight reduction that can be accomplished for less cost is profitable.

The table indicates that the mission equipment and power subsystems should be reduced in weight by 20%, communications and attitude control should not be changed, and propulsion and structure should be reduced 40%, producing a system weight of 573 pounds and a system unit cost of $11.3 x 10^6$. Compared to the cost resulting from a general weight reduction of 20%, the SCOT method produces a cost saving of $2.3 x 10^6$ per unit, or 20% of the program cost.

Choosing the Best Launch Vehicle

An extension of the SCOT method in which the overall program is unconstrained except for its desired results will minimize total program cost and choose the best launch vehicle available.

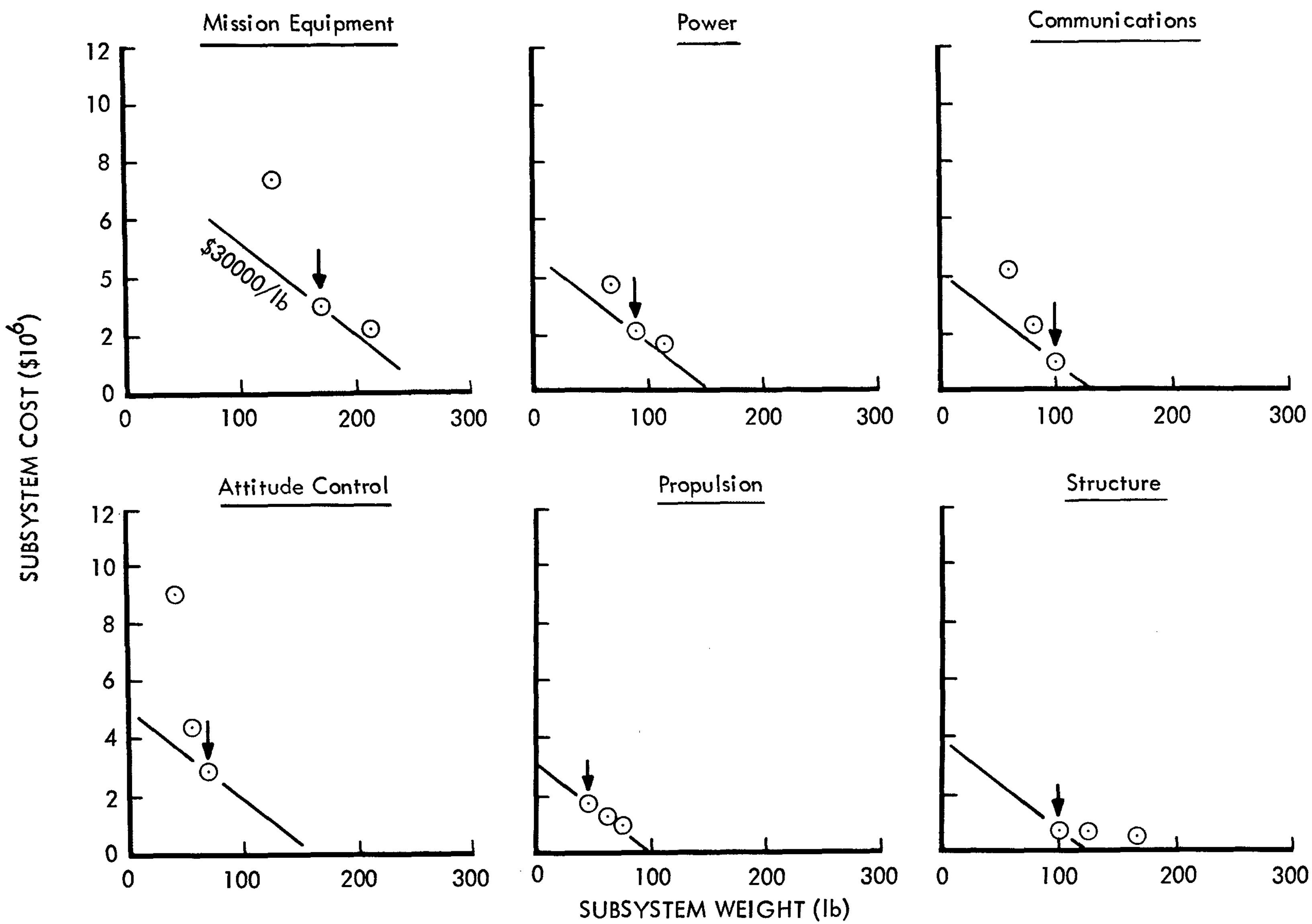


Figure 2.4-4: SPACECRAFT SUBSYSTEMS CANDIDATES

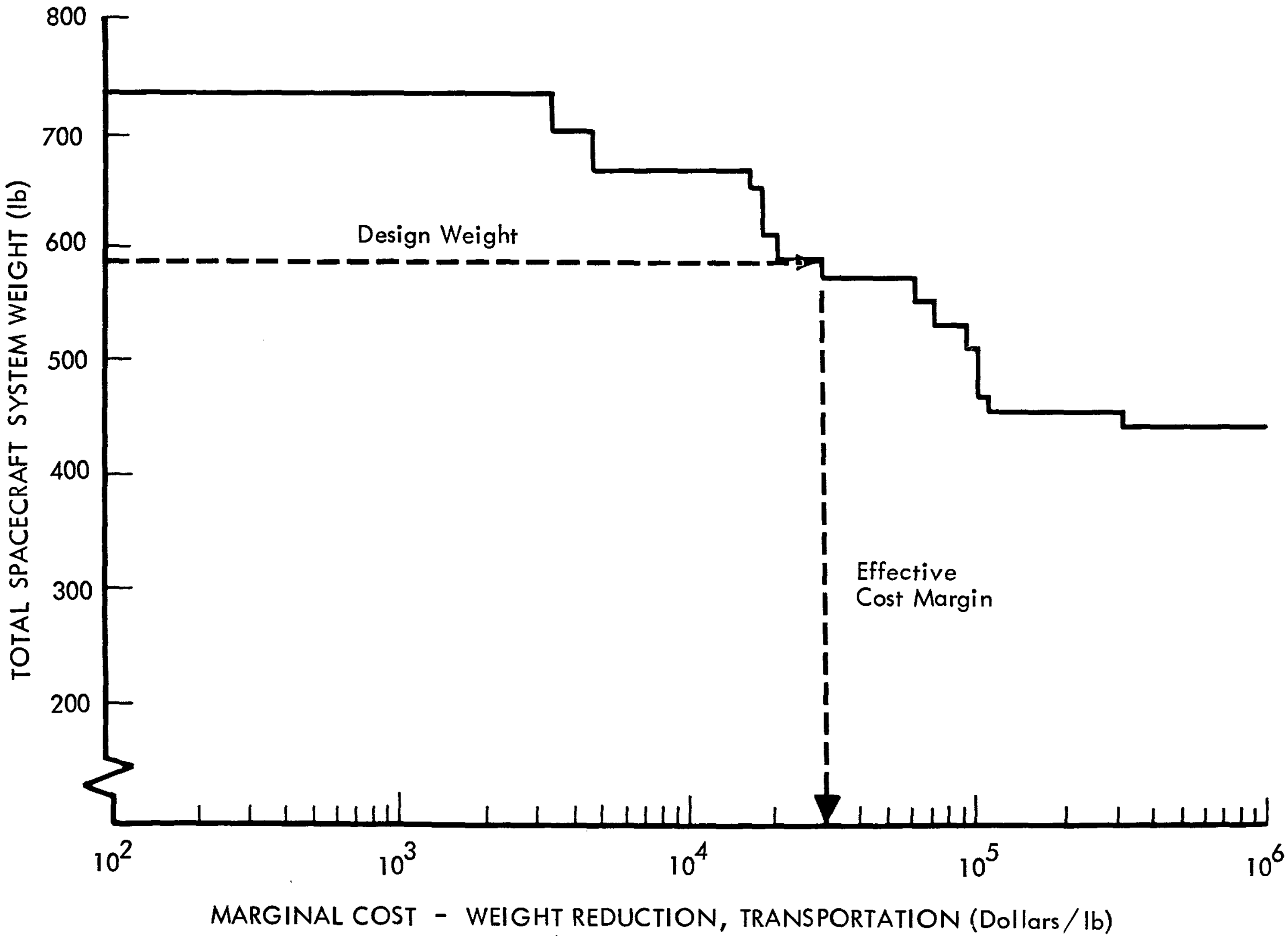


Figure 2.4-5: WEIGHT ALLOCATION OPTIMIZATION

The third problem posed was design of a new spacecraft for which a booster may be chosen from a number of alternates. The approach just discussed for Problem 2 also forms the initial steps for solving Problem 3. The data previously generated can be used to construct a curve showing total spacecraft cost as a function of total weight. Cost data can be shown on the same curve for boosters with a payload capability that spans the weight range for the spacecraft system. A total cost curve is generated by adding spacecraft and booster costs. The minimum total cost is then used to choose the booster, to define spacecraft weight, and to identify spacecraft cost. Finally, the plot of spacecraft weight against marginal cost (Figure 2.4-5) is used to identify the effective cost margin that provides an index from which to choose optimum subsystem candidates.

The same data used to construct Figure 2.4-5 can be extended to plot the spacecraft cost curve shown in Figure 2.4-6, if both spacecraft cost and weight are identified for each value of marginal cost. The choice of a booster using minimum program cost produces a total hardware cost of $\$14.8 \times 10^6$ at a spacecraft weight of 740 pounds. By comparison with the previous 573-pound design point, this represents a further cost saving of $\$0.8 \times 10^6$. The resulting spacecraft weight is used in Figure 2.4-5 to identify the effective cost margin ($3500/lb), which is then applied to Figure 2.4-4 to select optimum subsystems. In this case, the minimum cost system is one in which there are no weight reductions (off-the-shelf subsystems).

Research Implications of SCOT

The SCOT technique implies that past Earth-orbital hardware has been over-sophisticated, and it is often cheaper to provide a larger booster than a lighter-weight spacecraft.

Application of SCOT to a number of problems emphasizes the great differences between performance-optimized and cost-optimized designs. It has been shown that the marginal cost of removing weight from a typical small spacecraft can be one to three orders of magnitude greater than the marginal cost of transportation with which they should be matched for cost effective design.

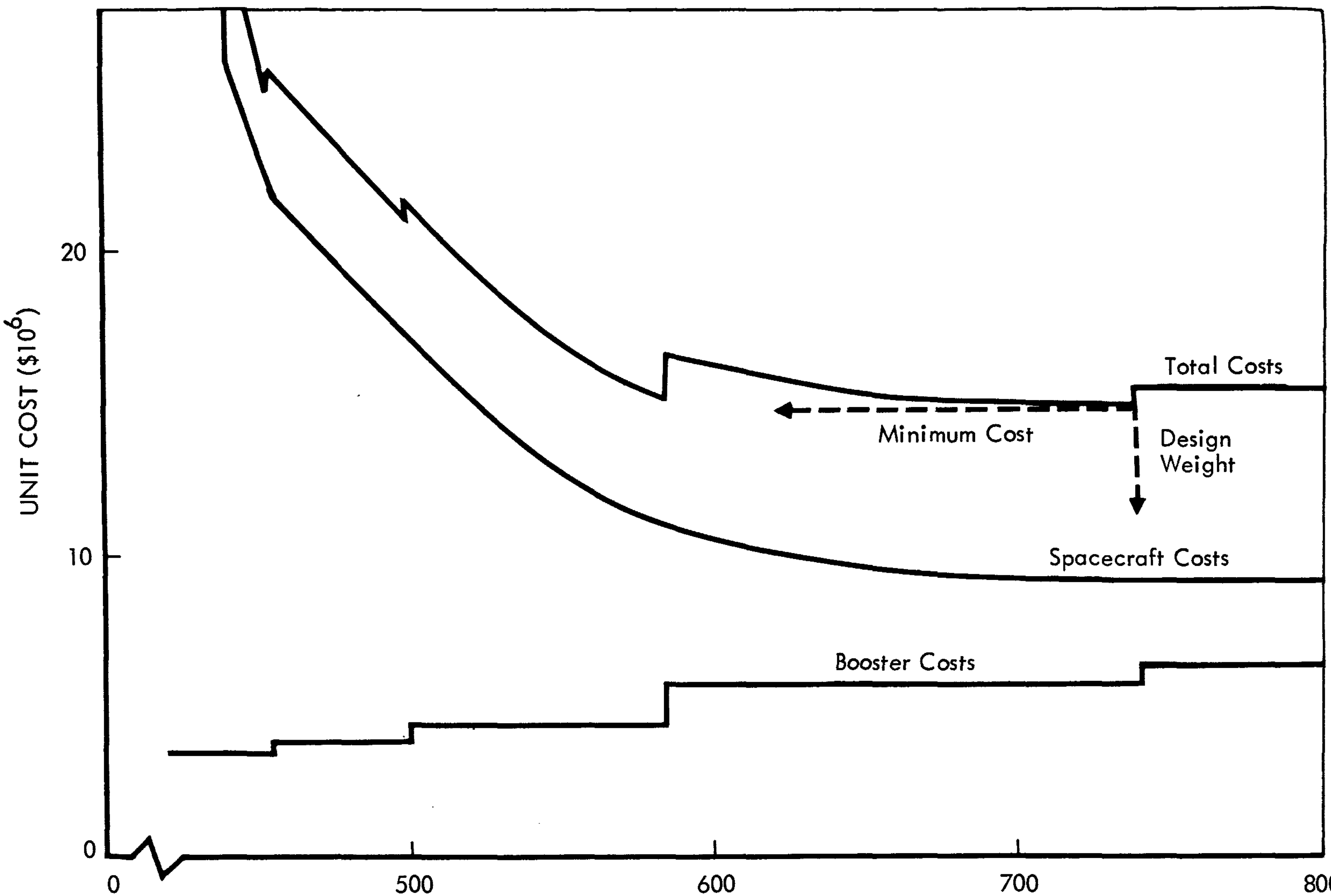


Figure 2.4-6: CHOICE OF OPTIMUM BOOSTER

Further, a deliberate, fact-based approach to weight allocation is required when the basis for allocation is economics.

SCOT shows that important cost savings can only be realized if costs are considered early in aerospace programs. As each major program decision becomes fixed, there is less latitude to save costs. Problem 2 showed that certain savings could be made within the weight limit of a certain booster. Problem 3 showed that the total program cost would be less if a larger booster could be used. The USAF Prime entry vehicle program is an example of the workability and success of the "large booster" rather than the "light spacecraft" program approach.

The higher marginal cost of subsystems other than structure points out the need for understanding their structural problems (load carrying, mode of failure, material selection).

2.5 CONFIGURATION BY ECONOMIC ANALYSIS

Cost Saving Through Reuse

The potential program cost savings that come from recovery and reuse of launch vehicle hardware cannot always be realized because of hidden costs that must be examined to determine when recovery is economically justified.

A typical space transport system consists of many functions and components that vary in economic value and in the time they are required (Figure 2.5-1). Configuration by economic analysis (CBEA) is a decision-making technique for launch vehicle design in which an economic decision is made to stage or retain components, and then to recover or expend them if staged. The method compares the net value of a recovered component with the value of a new one. The net value is computed by charging against the original component cost:

1) Cost of any acceleration not implicit in the component function, e.g., first-stage guidance carried with the second stage;
2) Cost of recovery device to return component;
3) Cost of accelerating recovery device to staging point of component;
4) Cost to refurbish component to a level comparable to that of new component.

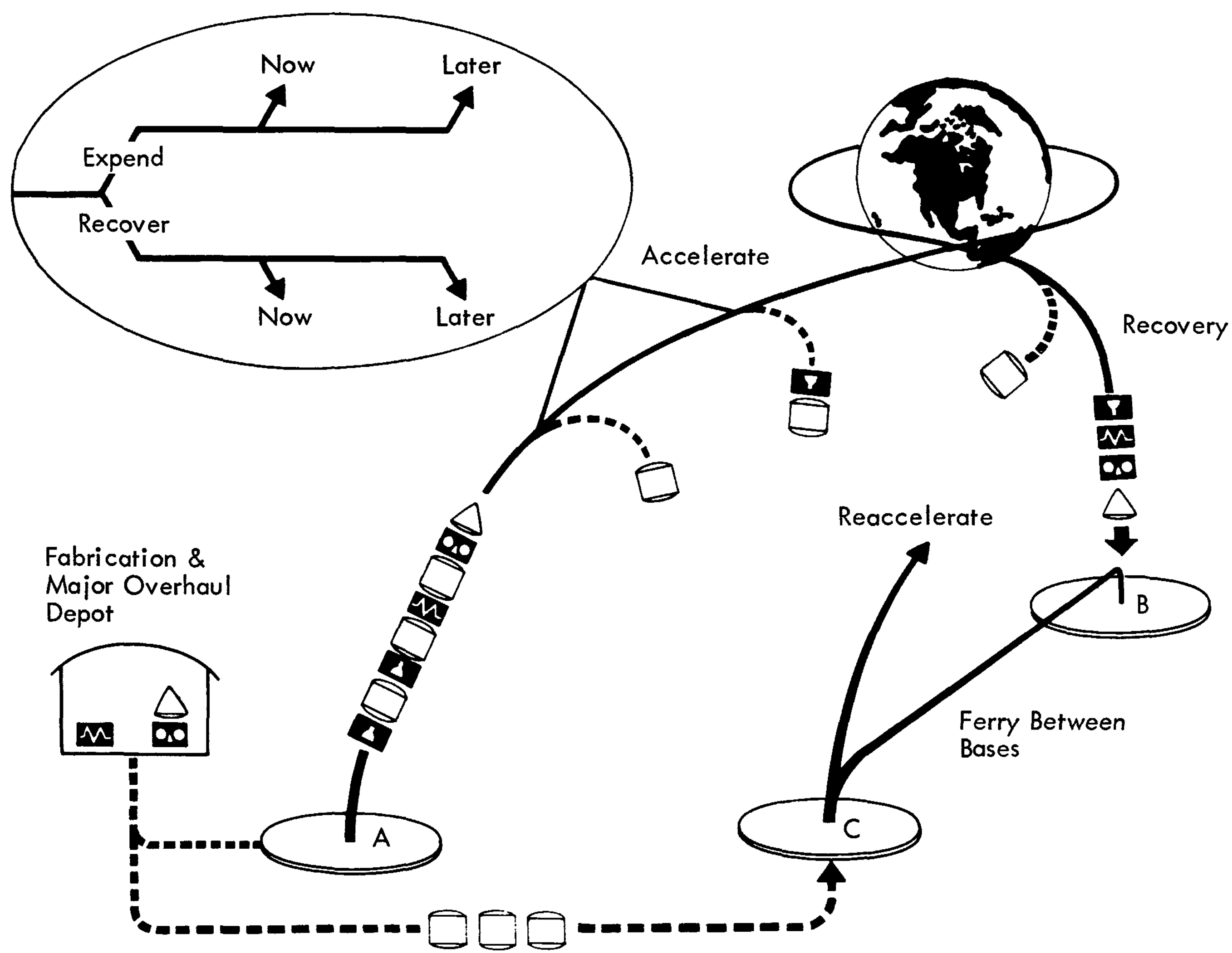


Figure 2.5-1: CONFIGURATION BY ECONOMIC ANALYSIS

If the net value is positive, recovery is economical; if negative, it is uneconomical.

Unique launch vehicle configurations result from application of this economic criterion. High-value components should be grouped together to facilitate recovery, and cheaper components should be staged as their function ends.

Cost of Expended Hardware

The total recurring cost of an item of expended launch vehicle equipment is the marginal cost of transporting the equipment plus the cost of buying the equipment.

Figure 2.5-2 shows the total recurring equipment-to-orbit (or payload) cost versus equipment (or payload) unit cost. The total recurring cost is a 45-degree slope line starting at the value of marginal transportation cost appropriate to the particular booster. Marginal transportation cost is the cost of changing the total launch vehicle inert weight (in orbit) by 1 pound. There is a further discussion of marginal transportation cost in Section 2.2 and a graphic representation on Figure 2.2-2.

Cost of Recovered Hardware

The total recurring cost of an item of recovered launch vehicle equipment is the sum of the marginal cost of transporting the equipment, the cost of the recovery device to return the item, the marginal cost of transporting the recovery device, and that portion of the equipment cost that needs to be prorated against each use.

Figure 2.5-3 shows total recurring equipment-to-orbit (or payload) cost versus equipment (or payload) unit cost, when the equipment is recovered and reused a number of times. In this case, the sloped line of total cost starts from a vertical axis intercept which accounts for both the marginal cost of transporting the equipment and recovery vehicle to orbit, and the cost of the recovery vehicle itself.

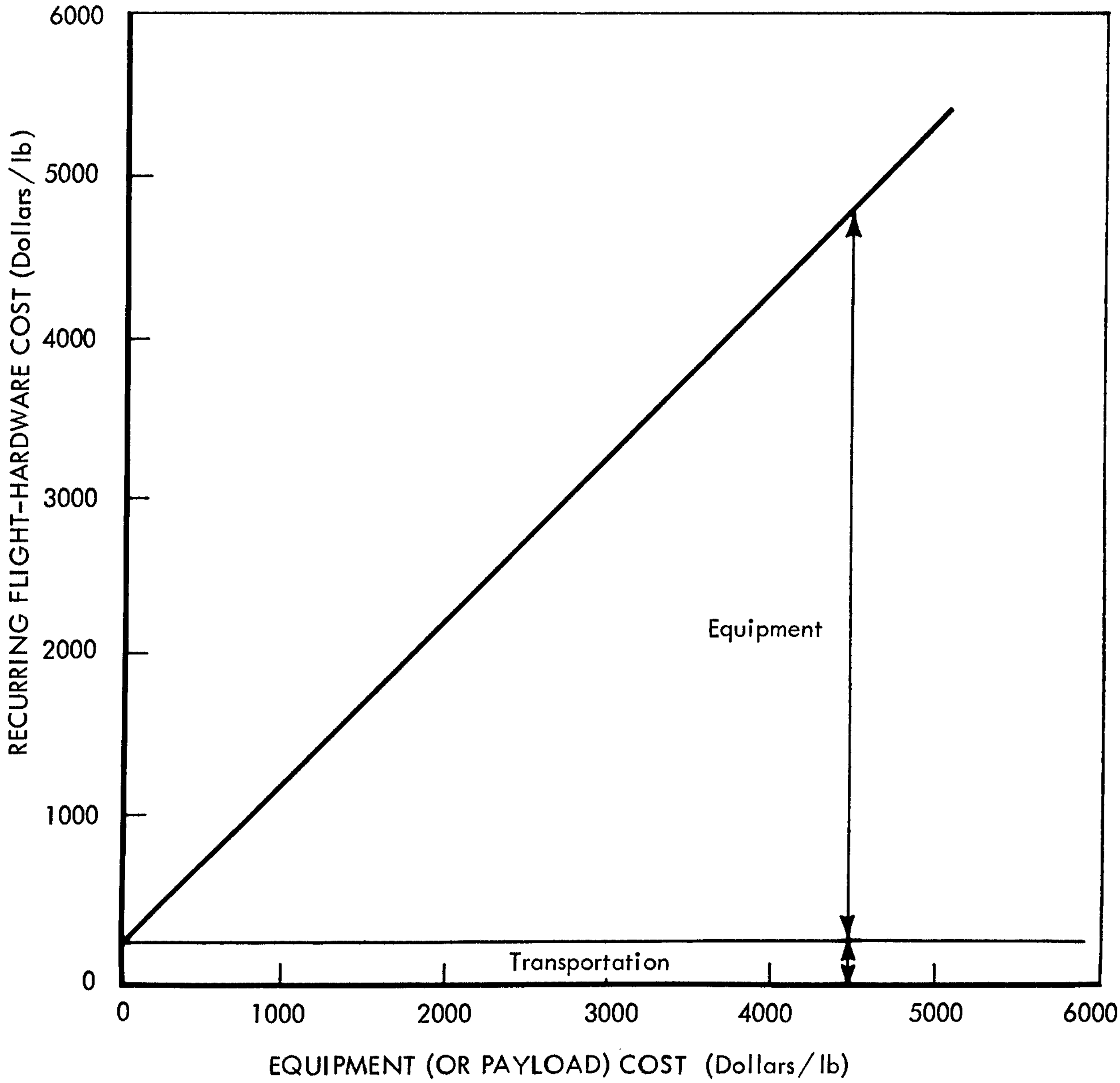


Figure 2.5-2: COST OF EXPENDED HARDWARE

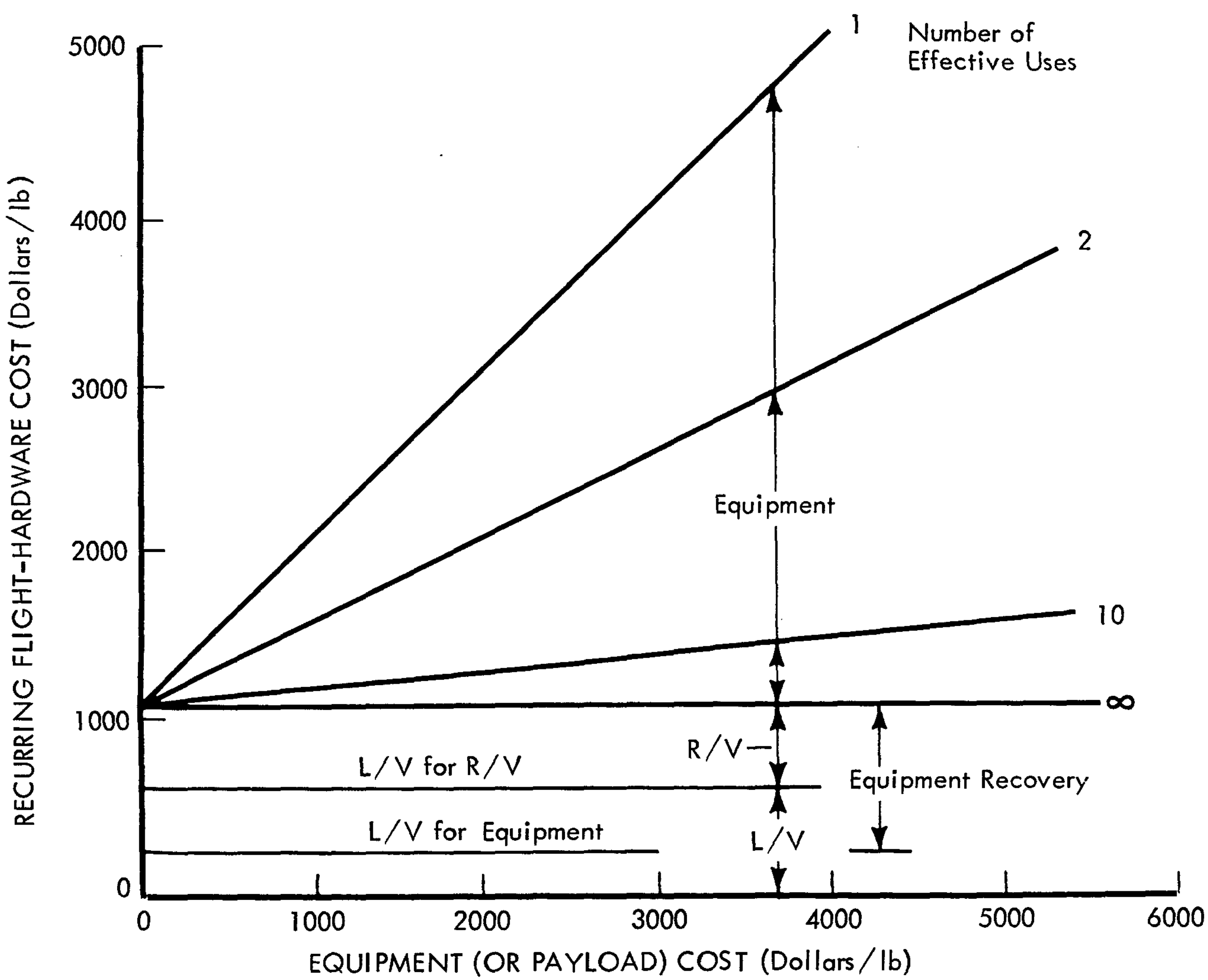


Figure 2.5-3: COST OF RECOVERED HARDWARE

The total cost is seen to vary with the number of effective uses of the equipment. The concept of effective uses is developed as the next topic. For the case of one use, the total cost line has a 45-degree slope just as in the expended hardware case, and the recovery vehicle investment is lost. For a large number of uses, the total cost line has a shallow slope and total cost can be a small fraction of the unit equipment cost.

Backup documentation (D2-114116-2) for this section contains two sample curves required for the generation of Figure 2.5-3. These two curves are recovery system weight and cost as functions of velocity.

"Effective Reuse" Concept

Since all recovered equipment requires maintenance, there is a maintenance cost incurred that can be applied to reduce the actual number of uses of an item of equipment so that there is an "effective number of uses" against which equipment cost can be prorated.

Effective uses, N_e, is defined by: $N_e = \frac{N}{1 + Nm}$

where: N = Actual flight reuses

$$m = \frac{\text{Maintenance cost per flight}}{\text{Initial cost}}$$

The above equation is plotted in Figure 2.5-4 for various values of m. Note that the lines for a given value of m are asymptotic to N_e equal to 1/m. For m = 0.02, the maximum value for N_e is 50 effective reuses. Furthermore, it takes 100 actual flights to reach a value of 33 effective reuses for the same 2% maintenance.

Studies have shown that entry vehicle maintenance costs are between 10 and 20% of initial entry vehicle cost. These values then imply a maximum value between 5 and 10 "effective reuses".

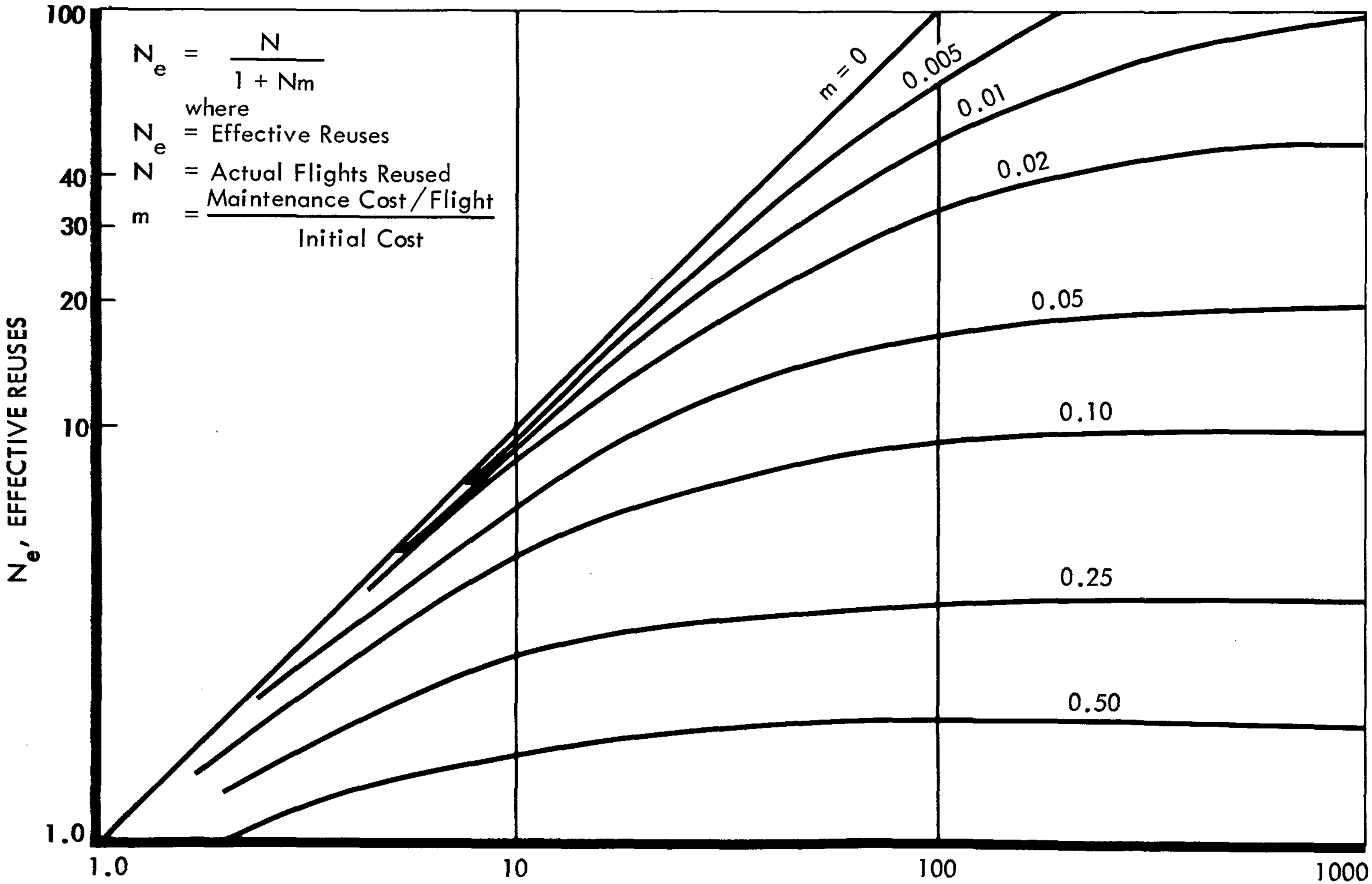


Figure 2.5-4: CONVERTING TO EFFECTIVE REUSES

Existence of Cost Break-Even

The nature of costs for expended equipment and for reused equipment is such that there always exists an equipment cost at which it is optional to expend or recover the equipment and beyond which equipment recovery is economical.

Figure 2.5-5 combines the expended and recovered equipment cases and depicts the equipment cost above which recovery is economical. The case shown is for orbital velocity, and a more general treatment of velocity will be developed. It should be noted that as long as N_e is greater than 1, the lines will always cross at some value of equipment cost. This occurs because any N_e greater than 1 implies a total cost line having a shallower slope than 45 degrees.

Effect of Velocity on Break-Even Equipment Cost

Because marginal transportation costs increase as the velocity to which equipment must be accelerated increases, the break-even equipment costs must also increase with this velocity.

Families of expendable and reused equipment cost lines are shown in Figure 2.5-6. The lines shown are for velocities from zero to orbital speed. The orbital velocity breakeven point has already been discussed. Similar breakeven points exist for lower velocities and are indicated on the figure. These latter intersections represent the equipment costs at which it is optional to recover or expend at suborbital velocities.

Another set of points is generated by the intersections of the orbital velocity reusable line and the suborbital expendable equipment cost lines. These intersections are the equipment costs at which it is optional to carry the equipment to orbit from the velocity noted (and recover it), or to expend it at the velocity in question.

Construction of Figure 2.5-6 requires consideration of the variation in transportation cost with velocity.

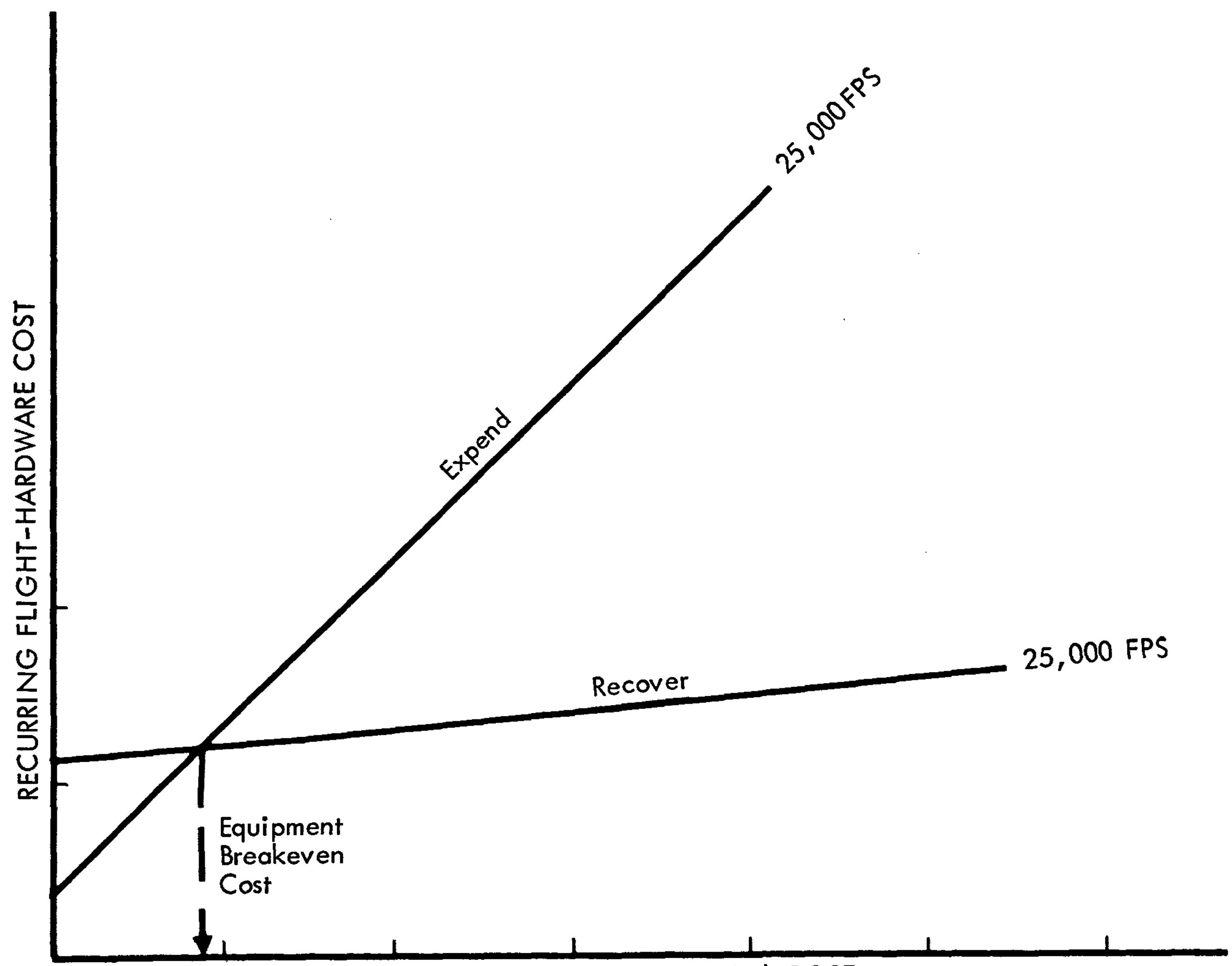


Figure 2.5-5: EXPEND-RECOVER BREAKEVEN POINT — ORBITAL VELOCITY

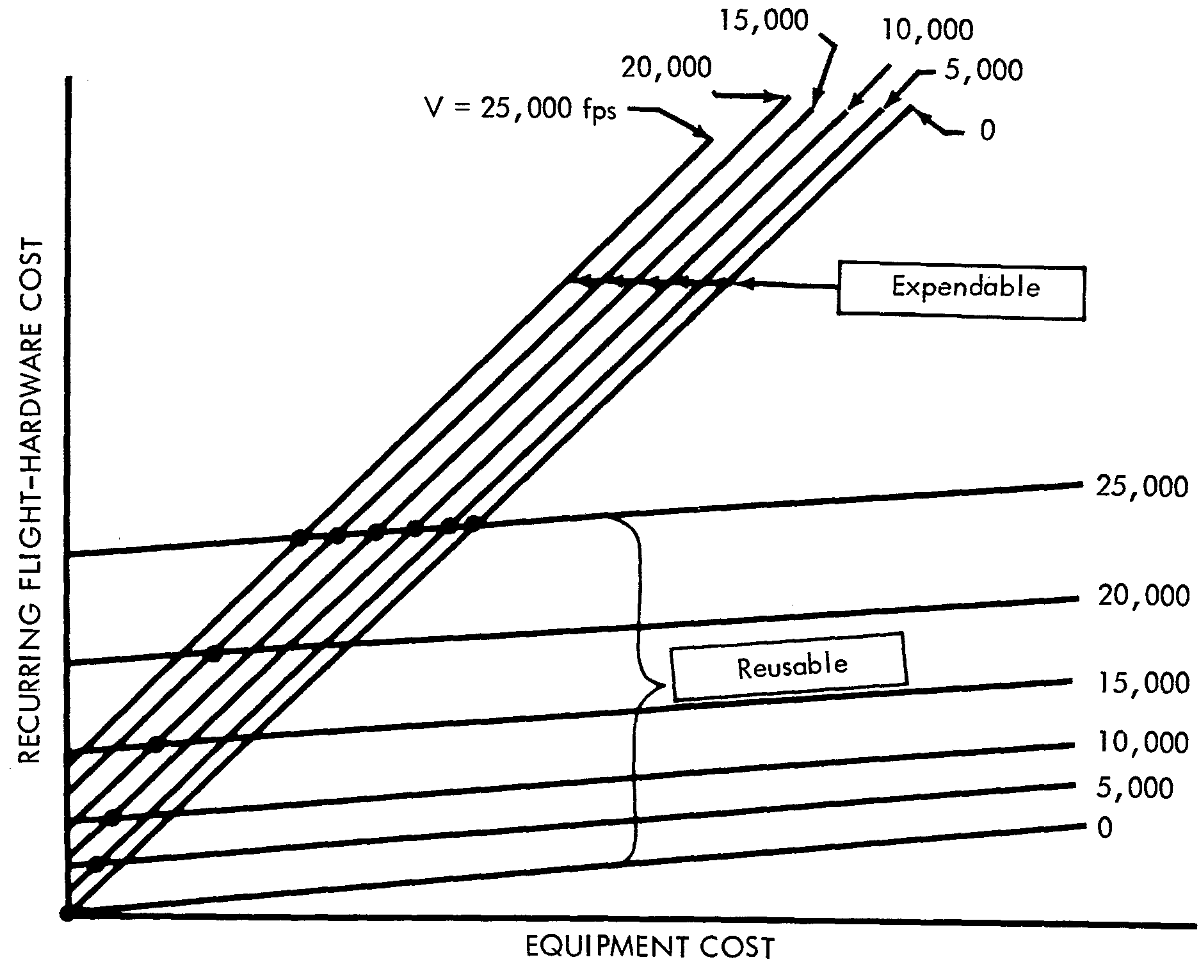


Figure 2.5-6: EXPEND-RECOVER BREAKEVEN POINT — SUBORBITAL VELOCITY

Economic Basis for Recovery Decision

A plot of equipment cost as a function of velocity provides a map by which the decision to recover equipment can be made.

Figure 2.5-7 shows the equipment breakeven cost-velocity relationship derived in the previous topic. The expend-recover decision curve has a lower part over which the equipment breakeven cost increases from zero to the orbital velocity value. The top of the decision curve is the locus of points representing carrying equipment to orbit and then recovering it.

Note that equipment cost is the ordinate of Figure 2.5-7. This cost is the total cost of a piece of equipment including purchase, installation, and checkout. Such costs require the allocation of what are frequently termed "nondistributable" costs to the subsystem level. For equipment costs below the lower branch of the decision curve, the equipment should be expended when its function is completed. For equipment cost between the two curves, equipment should be recovered from the velocity at which its function ceases. For equipment cost above the two curves, recovery is even more economical and may be deferred until reaching orbital velocity.

A decision curve, such as Figure 2.5-7, is a function of marginal transportation cost versus velocity, number of equipment and recovery vehicle reuses, recovery vehicle cost, and the ratio of recovery system weight to recovered weight.

Research Implications for Recoverable Boosters

The use of known cost, weight, and maintenance data in forming a recovery decision map, together with the current level of equipment costs, shows that fully recoverable boosters are not economically justified, but that boosters should be configured so that electronics and turbomachinery can be recovered and reused.

Cost decision curves are shown in Figure 2.5-8 for four values of recovery vehicle effective reuses. The other assumptions are noted on the figure.

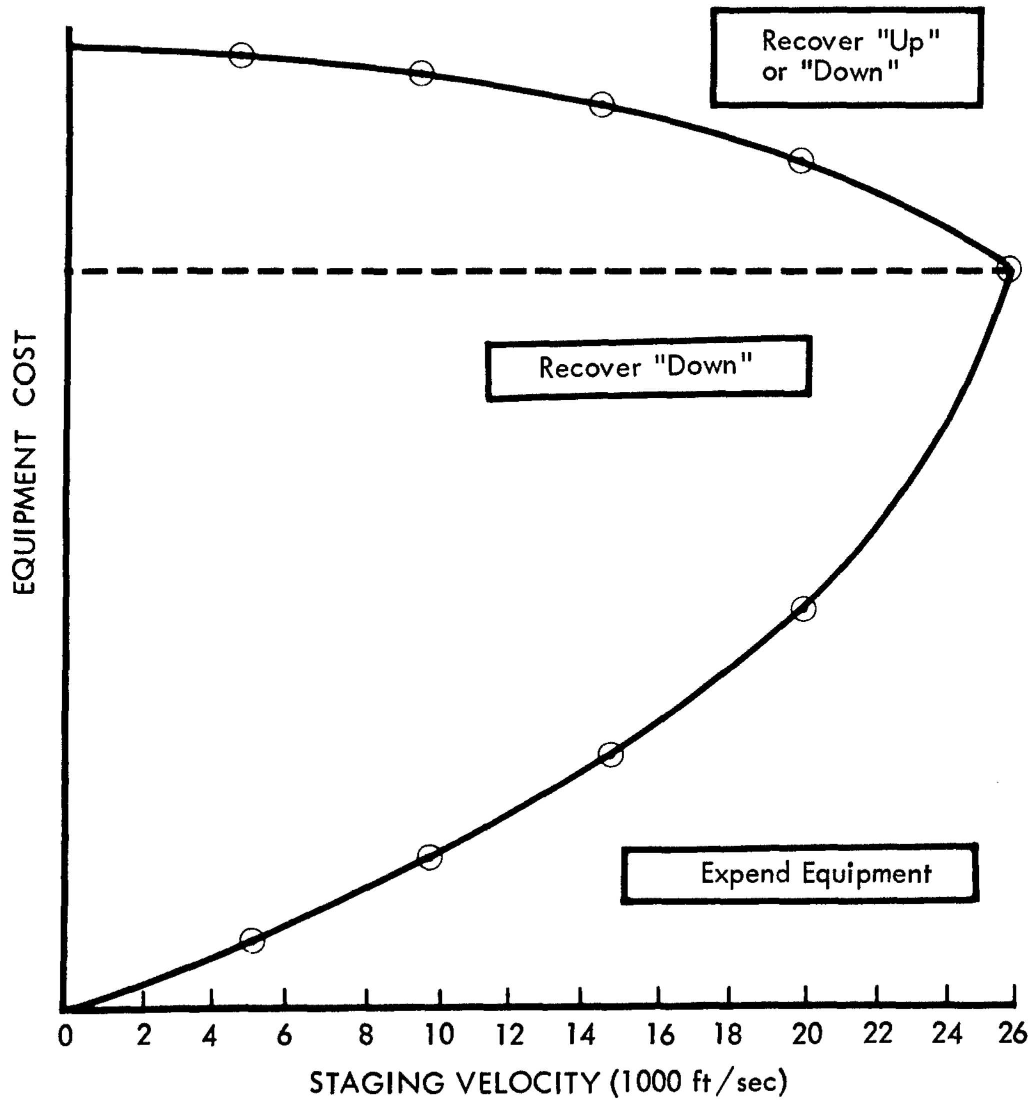


Figure 2.5-7: EXPEND-RECOVER DECISION CURVE

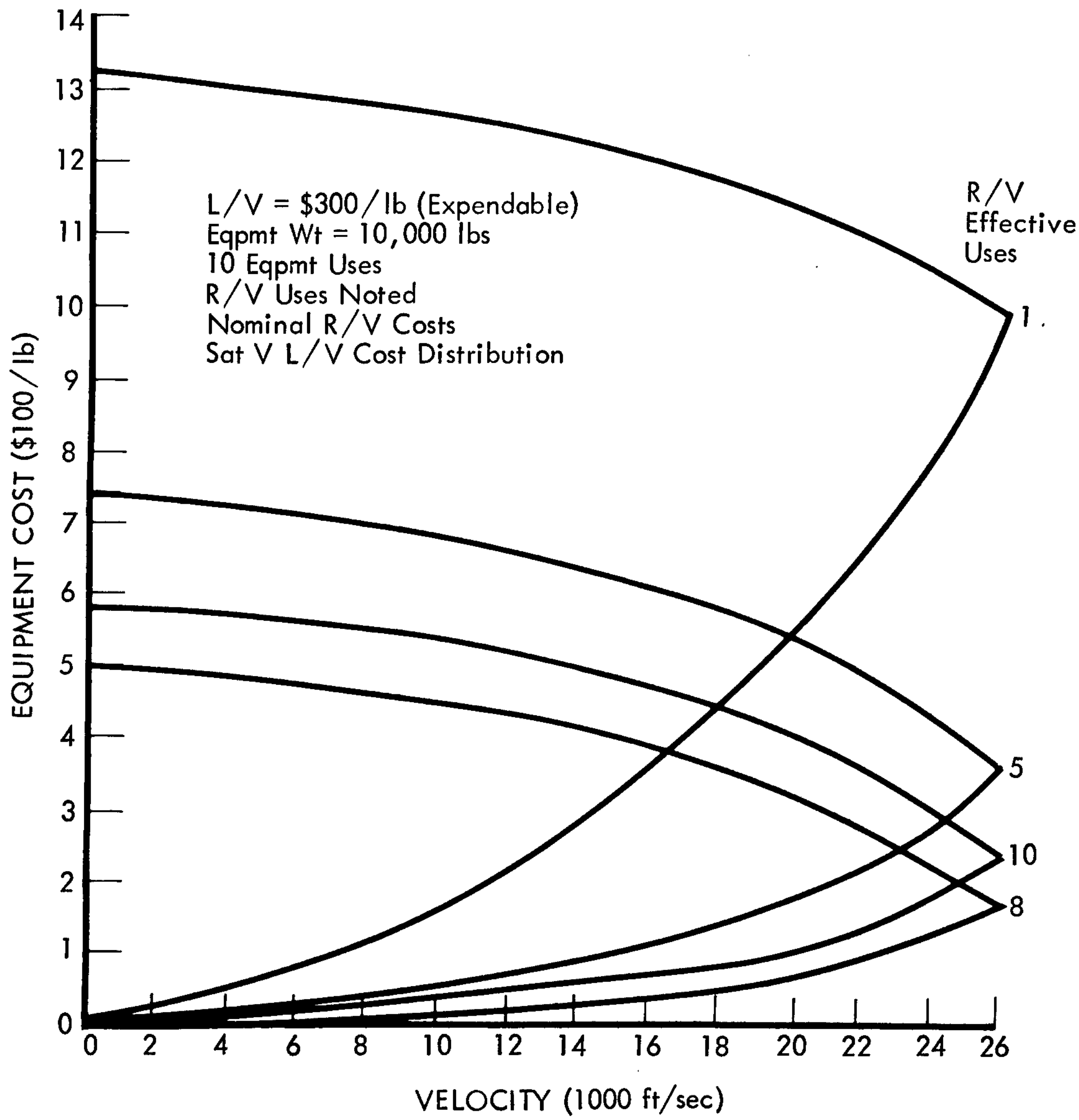


Figure 2.5-8: DECISION CURVE USING ACTUAL DATA

The equipment cost at which orbital recovery is economical drops from \$1000/lb to \$250/lb as recovery vehicle uses rise from 1 to 10. A larger number of effective uses has a small effect on equipment cost. At a staging velocity of 8000 ft/sec, recovery is economical for equipment (hardware) having a cost as low as \$25/lb, if 10 recovery vehicle uses can be assumed.

Recovery vehicle reuse is seen to be a powerful factor in determining the economical reuse of launch vehicle equipment and payload. Maintenance costs per flight of 10 to 20% of recovery vehicle cost appear to be realistic, at least for a first-generation system. Thermal protection system refurbishment studies should continue and be broadened from the per-square-foot category. The maintenance cost of the entire recovery vehicle must be examined with special emphasis on the inspection of substructure and the requalification necessary before reuse.

Research efforts should also be directed at the configuration and packaging of expensive launch vehicle components so that they can be recovered and reused without extensive retesting.

3.0 STRUCTURES AND MATERIALS STUDIES

Application to Structures Areas

Cost comparisons were made in four typical structures areas to illustrate application of techniques and derive possible research direction.

In this section, the methods of economic analysis outlined in Section 2.0 are applied. Four examples were selected for this summary document: thermal protection systems, material trades, cryogenic containment concepts---lunar, and pressure-fed launch vehicle stage materials.

These four topics were selected because data were available. The first, third, and fourth examples will use the SCOT plot to show the cost-weight balance. The second example, material trades, introduces cost into material efficiency considerations.

3.1 THERMAL PROTECTION SYSTEMS

Existence of Trades

The two basic methods of handling entry vehicle heating---material phase change and reradiation---each show economic advantages for some applications.

Much work has been done on manned entry spacecraft thermal protection systems from the standpoint of solving the extremely difficult technical problems brought about by the environment. The success of Mercury, Gemini, Asset, and Prime in entering from, or near, low Earth-orbit entry velocity, and Apollo 4 in entering from lunar return speed, shows the industry capability in thermal protection.

Gemini and Mercury had hybrid thermal protection systems, both ablation and radiation structure, whereas Asset had both metallic and ceramic radiation structure. The Apollo command module and the Prime vehicle are covered exclusively with ablation material. It is evident that technical considerations, which have controlled the design of thermal protection systems to date, lead to trade-offs between various concepts.

To date, cost has been a weak factor in thermal protection system design compared to a justified concern for reliability and safety. As entry technology and mission traffic advances, cost will become increasingly important. Entry vehicle development, recurring, and refurbishment costs must be well understood and the cost-weight balance established for their structural systems.

Structural Concepts Considered

Ablation, radiation, and transpiration thermal protection structural concepts were considered and costed so that economic comparisons could be made.

Figure 3.1-1 illustrates the three thermal protection system concepts studied. Note that the backwall temperature was held to 200°F.

The radiation concept shown is similar to that developed for the X-20 (Dyna-Soar), except that the "hot" corrugated Rene' 41 panels are replaced by a water-cooled aluminum structure. The heat shields and support clips are coated columbium; the insulation is stabilized Q-felt. Lower-temperature areas use superalloy (Rene' 41) as the reradiant surface.

Low-density phenolic nylon and silicone elastomeric materials were considered for ablation thermal protection. Some consideration was given to cork because of its low cost and successful use on the Minuteman ICBM. Refurbishable ablation concepts proposed by AVCO and The Martin Company (References 5 and 6) were compared. The AVCO design involved postflight machining of residual ablation material and recoating the substrate. Martin proposed removable honeycomb panels that were to be discarded and replaced after each flight.

Transpiration cooling is much less developed than the other two concepts. Coated refractory, a high-temperature insulation, and a flow control barrier are required, and some form, usually active, of transpirant flow control system is needed. Transpiration is attractive because of its potentially low refurbishment cost, its adaptability to a broad range of

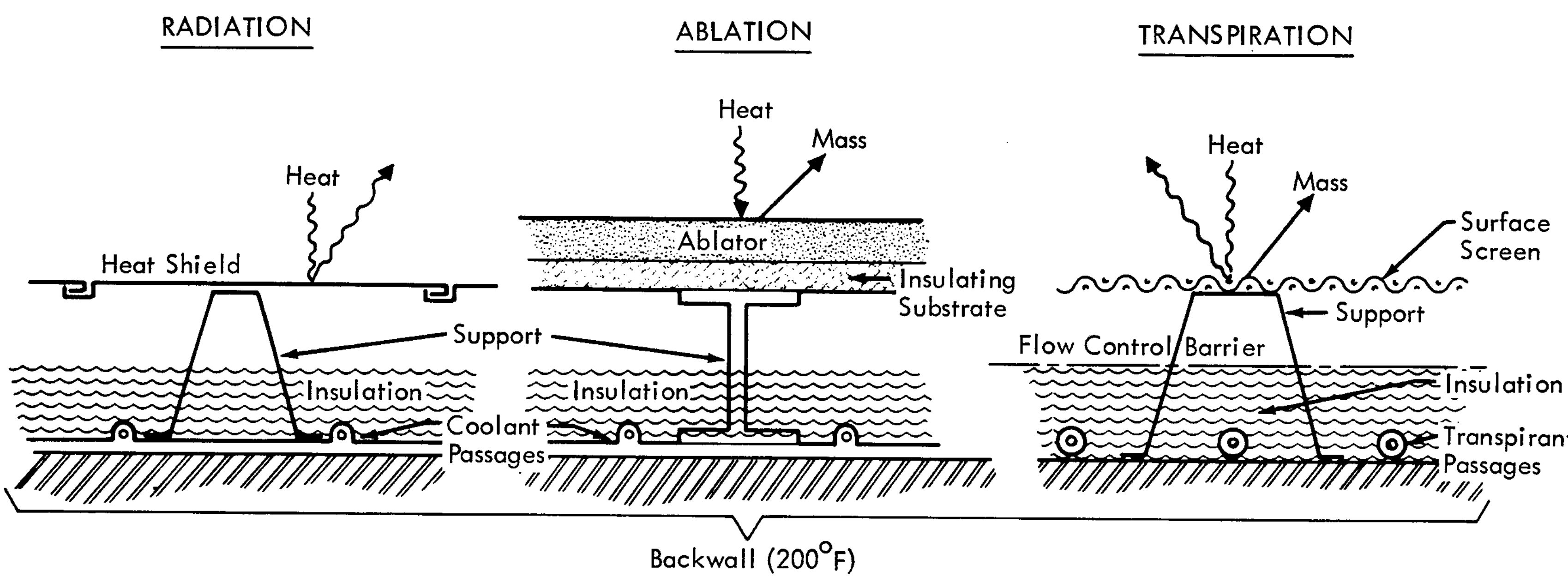


Figure 3.1-1: THERMAL PROTECTION CONCEPTS

heat inputs, and its promise of configuration shape retention. Transpiration system details were taken from work done under Contract NAS2-3443 (Reference 7).

Cost Data

Radiation, ablation, and transpiration cost data suitable for economic comparison were obtained from Boeing studies and other published data.

As part of the "Cost Effective Structures Design for Future Space Systems" study, actual production drawings and manufacturing and tooling experience on the X-20 were used to estimate the manufacturing costs for a lower wing heat shield assembly. Cost estimates were made for part fabrication as well as for subassembly and assembly operations, including quality control. These X-20 data were used to estimate similar costs for the radiation concept shown at the left in Figure 3.1-1. This detailed costing yielded the columbium radiation unit cost data of Figure 3.1-2. The costs shown for tantalum and Rene' 41 are scaled from the columbium data.

Figure 3.1-2 presents ablation unit costs for low-density phenolic nylon and silicone elastometers. These data are from Martin reports (Reference 6) and are the average for application to fiberglass face and core honeycomb and steel-face/glass-core honeycomb. Cork costs are from Boeing Minuteman data. Inspection is included in these costs.

Transpiration system costs are derived from work done under NASA Contract NAS2-3443 (Reference 7). A manufacturing cost estimate of a detailed design was made as part of the cost effective structures contract. The transpiration system cost must be regarded as a preliminary estimate pending more thorough demonstration of such a system.

Thermal protection system maintenance is shown in the middle data columns of Figure 3.1-2. The value shown, m, is maintenance cost per flight divided by initial hardware cost.

CONCEPT		UNIT COST ($/sq ft)	MAINTENANCE	R&D $ (comparable development)
ABLATION	PHENOLIC NYLON	1160	0.74	5,000,000
	SILICONE ELASTOMERS	737	0.47	4,000,000
	CORK	96	1.30	2,000,000
RADIATION	RENE' 41	1650	0.02	2,000,000
	COLUMBIUM	2070	0.15	6,000,000
	TANTALUM	2500	0.33	8,000,000
TRANSPIRATION	(2700°F Cb)	2180	0.04	10,000,000

Figure 3.1-2: THERMAL PROTECTION COST PARAMETER SUMMARY

Phenolic nylon and silicone elastomer maintenance estimates are derived from AVCO data. The reduction in m from 0.74 to 0.47 is due to an assumption that m is proportional to panel initial cost to reflect the relative handling ease of the silicone material. Cork is assumed to be bonded directly to the substructure and to require 30% of its application cost for stripping.

The columbium radiation maintenance data is derived from McDonnell estimates (Reference 8). The tantalum value of m - 0.33 assumes a life of three entry cycles (L/D = 1) for coated tantalum at 3400°F. Transpiration system maintenance is considered to be keyed to the refractory, which is derated to 2700°F maximum temperature.

The far-right column in Figure 3.1-2 is an estimate of dollars required to bring the thermal protection systems to a comparable state of development. These estimates have *not* been substantiated by a detailed examination of the required development programs.

SCOT Comparisons

SCOT comparisons demonstrate the relative economic merit of the thermal protection systems because they solve the cost-weight equation for candidates having equal function.

Thermal protection system unit cost is shown in Figure 3.1-3 on a cost-weight plot. The figure is drawn for a low-Earth-orbit entry vehicle, a flying equilibrium glide, and a hypersonic L/D = 1. The unit cost is the average over a 180-flight program and accounts for recurring cost, maintenance, and the development costs of Figure 3.1-2, prorated. Vehicle maintenance was introduced by considering an expendable and a 50-use system. The entry vehicle was considered to have 250 ft^2 of wetted area subjected to each of the two peak heating rates shown. An additional 10 ft^2 of wetted area, at 80 Btu/ft^2sec, is considered in the backup material.

Two marginal transportation costs were assumed in making the SCOT comparisons. Four conclusions can be drawn from Figure 3.1-3 and companion data:

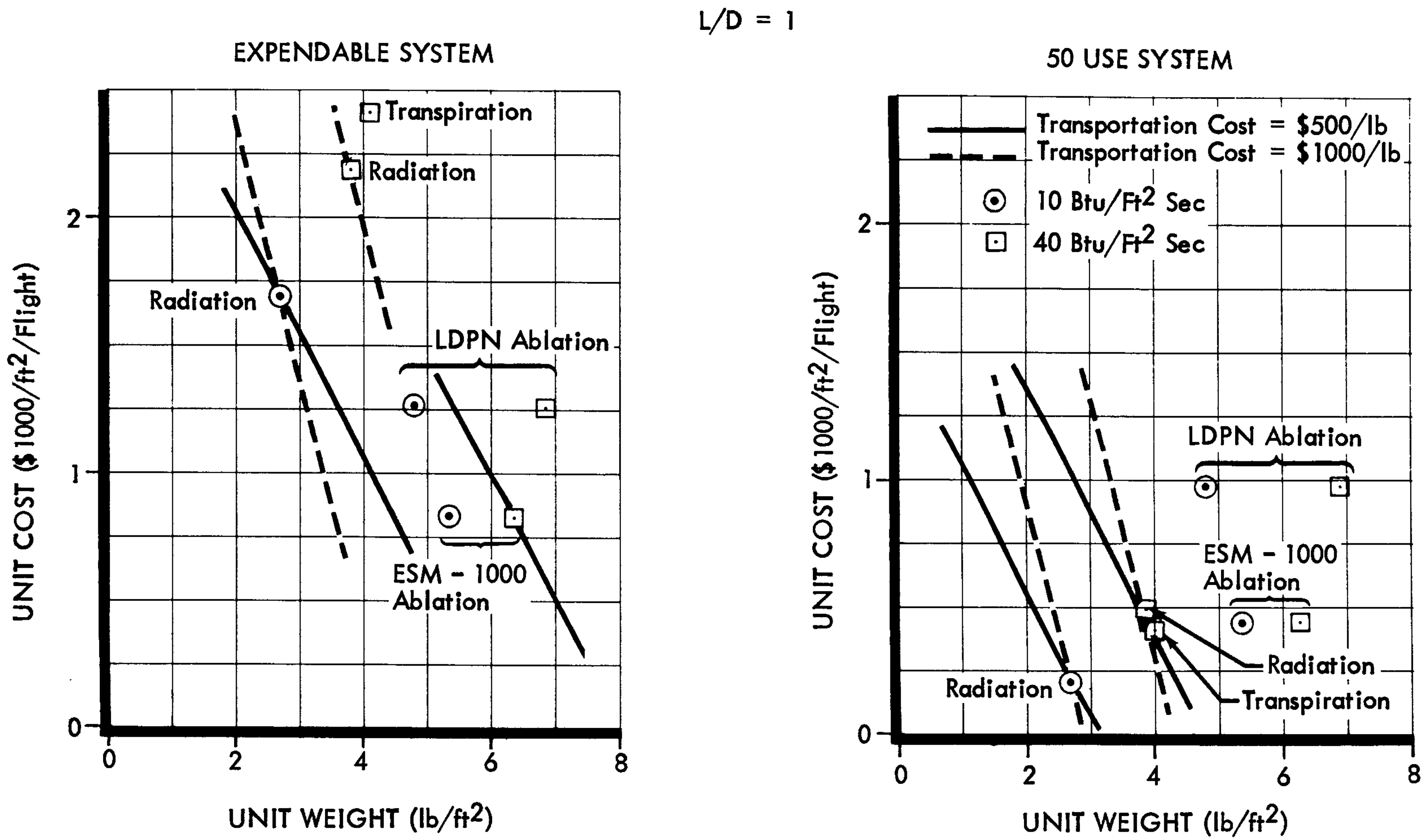


Figure 3.1-3: THERMAL PROTECTION SYSTEM EFFICIENCY

1) Low-density phenolic nylon is never cost effective.

2) ESM-1000 ablation is cost effective for expendable low and medium L/D vehicles, for heating rates above 40 Btu/ft^{2}sec.

3) Transpiration is not cost effective for low and medium L/D vehicles, either expendable or having 50-use capability, except in a region of high heating rate on the low L/D, 50-use configuration.

4) Radiation is always most cost-effective at lower heating rates for both expendable and 50-use, low L/D vehicles at a marginal transportation cost of $1000/lb, and nearly always at $500/lb. Radiation, used for the 80 Btu/ft^{2}sec area, was cost-effective for L/D = 1, but not for L/D = 0.5.

Research Implications

The economic merit of thermal protection system candidates leads to conclusions on research to be pursued for specific applications.

Most of the entry vehicle mission requirements foreseen in the near future can be accomplished by a low to medium L/D configuration. This point is discussed in Section 4.1 of this document. No positive proof can be offered, but it is probable that mission traffic will eventually be high enough to warrant the use of multipurpose and multiuse entry vehicles. It is also probable that any new, maneuverable, reusable entry vehicle would be operational before 1975. Design of such a vehicle to suit both NASA and DOD requirements appears likely.

In any case, continued research on silicone elastomeric ablation materials is warranted, with emphasis on cost reduction through elimination of the loaded honeycomb feature by use of a mechanically stronger ablator. A variable-density ablator, with density decreasing inward from the surface, would merge the mass loss and insulation functions and reduce substrate costs. Reuse studies should stress the saving of high-cost substructure as a necessity to cost effectiveness.

A modest level of radiation structure research also seems justified. The extensive use of radiation structure on lower L/D vehicles, its probable use on vehicles having an L/D of 1.5 or greater, and the inherent advantages of a fixed contour argue this point. A better understanding of the greatly improved columbium alloys (such as C-129Y) should be gained. Tantalum coating should be pursued to demonstrate a 3400°F system, but no pressing need is seen for extensive tantalum component development at this time.

Nondestructuve methods should be found for determining the remaining life of a refractory component that has been subjected to the entry environment.

It is also felt that entry environment simulation for test should have further research. Specific thought should be given to means of accelerated life testing.

Some continuing study should be given to transpiration cooling. System demonstration is still the major problem. Transpirants such as lithium, hydrogen, and ammonia deserve further consideration from a feasibility, if not a cost effective, standpoint.

3.2 MATERIAL TRADES

Importance of Material Selection

The proper economic choice of materials for specific applications is necessary early in development programs to avoid unjustified oversophistication and to ensure that the problems of using high-performance materials are not encountered unnecessarily.

In designing structural hardware, it is important to choose materials early. Figure 3.2-1, a conventional strength/weight comparison of materials for various temperatures, shows some of the many choices confronting a designer. Even when other environmental considerations, such as chemical compatability or the presence of stress cycles, place limitations on material application, many alternatives can exist.

In general, materials show some variation in raw material costs and a wide variation in fabrication costs. Furthermore, new materials are appearing that, although having high performance, are both expensive to buy and to fabricate (for example, whisker composites).

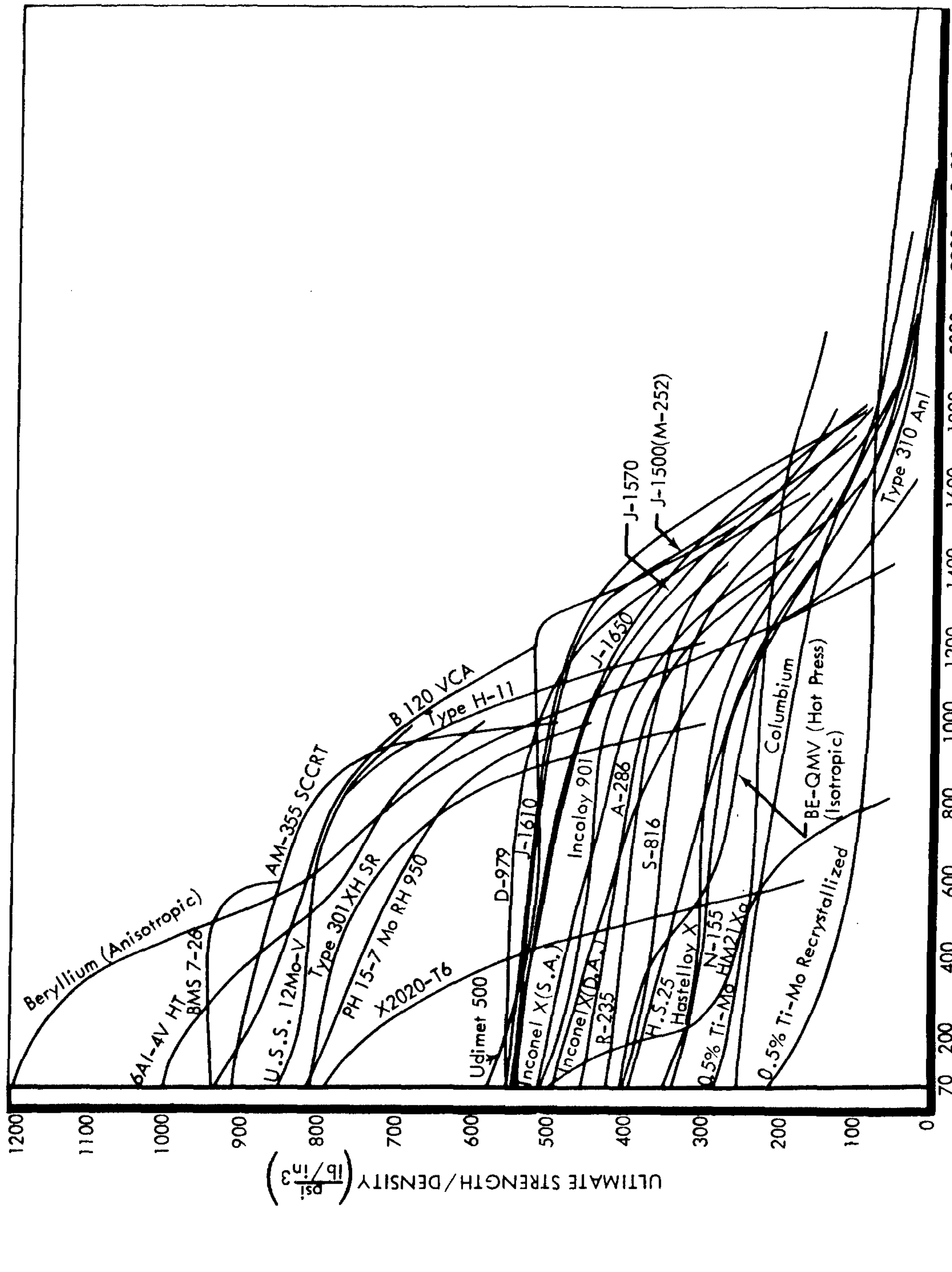


Figure 3.2-1: MATERIALS COMPARISON

The material choice can have an extensive impact on program costs because: fabrication costs are a "driver" of software costs; the use of a high-performance material can dictate extensive material developments and demonstration testing; and material choice may dictate or limit fabrication concepts.

Adding the Cost Dimension to Material Selection

The traditional approach to material trades using structural weight parameters can be extended to cost trades with available data by including the raw material cost, fabrication cost, and economic utility of weight.

The well-known structural optimization techniques of Gerard (Reference 9) and others are capable of comparing materials on a weight basis for any specified application. To extend such techniques to cost trades, it is necessary only to evaluate the total material cost per unit weight. This cost is made up of the cost to buy, the cost to fabricate, and the cost to transport the material on a per-pound basis.

The purchase cost of raw material is easily obtained if the specific application is known. To perform general comparison, it can be estimated with fair accuracy by considering a representative size of order and representative selection of structural forms. The column labeled C_p in Figure 3.2-2 lists this quantity for several alloys.

Similarly, fabrication cost can be estimated if the specific application is defined. To generalize: A selection of fabrication processes is chosen and an average manufacturing cost is established. This cost, for the same materials, is tabulated under $K_F C_A$ in Figure 3.2-2.

The economic utility of weight, as discussed in Section 2.2, is given by marginal transportation cost. Using two values, \$100/lb and \$1000/lb, the last two columns tabulate total material costs (per cubic inch) in dollars.

Material	C_P (\$/lb)	$K_F C_A$ (\$/lb)	Total Cost Parameter (\$/in^3)	
			C_B = \$100/lb	C_B = \$1000/lb
Aluminum				
2024-T6	0.51	105	20	100
2219-T62	0.66	105	21	113
7075-T6	0.66	105	21	112
Magnesium HK31A	4.90	165	17	75
Stainless 301 XHSR	1.00	113	62	323
Steel 4340	0.18	140	68	323
Titanium 6AL-4V	11.15	227	52	196
Superalloy Rene'41	9.00	125	67	336
Beryllium Hot Press	360.00	656	50	110
Columbium FS 82	80.00	188	107	441
Fiberglass Epoxy	5.31	165	18	77

Figure 3.2-2: MATERIAL COST PARAMETERS

Manufacturing Complexity

The fabrication cost of a material is represented by a manufacturing complexity factor, which is the fabrication cost for that material relative to a common aluminum alloy.

The aerospace industry is most familiar with the fabrication of aluminum alloys. Therefore, it is convenient to reference the cost of fabrication processes for other materials to equivalent cost for aluminum. This ratio is called the manufacturing complexity factor. The fabrication costs tabulated in Figure 3.2-2 were generated in this manner. In the figure, K_F is the complexity factor, and C_A is a baseline aluminum fabrication cost.

The complexity factors are weighted averages over a number of representative fabrication processes tabulated in Figure 3.2-3. Not all of these processes apply to all of the materials, so suitable substitutions were made. For example, if the material is not subject to heat treatment, an equivalent cold-working process was substituted.

The Material-Geometry Index

The interaction of various material properties in structural design requires that each structural geometry be treated separately to determine the appropriate structural index.

Material properties interact with each other, and with component geometry, in defining the quantity of a material required to satisfy a structural requirement. Consequently, the merits of materials must be considered for each geometry. Compression-loaded designs require stiffness, whereas tension-loaded designs require strength. Ultimate strength designs must consider safety margins and failure modes in deciding which properties are critical.

Figure 3.2-4 presents the derivation of a simple structural index---that for a monocoque cylinder in compression. The cylinder is assumed to be thin, so that the failure will be perfectly elastic and only Young's

	Forming		Metal Removal -	Trim -	Joining -	Heat Treat		Cold Work -	Weighted
	Hydro Press	Brake	Chem Mill	Shear	E.B. Weld	Quench	Age	Stretch	Average
Aluminum									
2024-T62	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.30
2219-T62	1.0	1.0	1.0	1.0	2.0	1.0	2.0	1.0	1.30
7075-T6	1.5	1.0	1.0	1.0	2.0	1.0	2.0	1.0	1.30
Magnesium HK 31A	3.0	1.0	1.0	1.0	4.0	N.A.	N.A.	3.0	2.00
Stainless 301 XHSR	1.5*	1.0*	1.5	2.0	1.0	N.A.	N.A.	1.5	1.40
Steel 4340	1.5	1.0	N.A.	1.5	1.0	2.0	N.A.	2.0	1.75
Titanium 6Al-4V	6.0	3.0	1.5	2.0	3.0	1.0	2.0	5.0	2.70
Superalloy Rene' 41	1.5	1.0	1.5	2.5	2.0	1.0	2.0	1.5	1.45
Beryllium Hot Press	10.0	3.0	1.0	3.0	1.5**	N.A.	N.A.	N.A.	3.70
Columbium FS 82	1.5	1.0	1.0	1.5	1.0	N.A.	N.A.	2.0	1.35
Fiberglass Epoxy Resin	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	2.00

*Annealed Condition
**Furnace Braze
N.A. = Not Applicable

Figure 3.2-3: MATERIAL COMPLEXITY FACTORS

FAILURE STRESS:

$$\sigma_{CR} = KE \left(\frac{t}{R}\right)^{1.6}$$

APPLIED STRESS:

$$\sigma = \frac{P}{A} = \frac{P}{2\pi Rt} = \sigma_{CR}$$

RESULTING GAGE:

$$t = \left(\frac{PR}{2\pi KE}\right)^{1/2.6}$$

MATERIAL GEOMETRY INDEX:

$$MG = t / \left(\frac{PR}{2\pi K}\right)^{1/2.6} = 1/E^{0.385}$$

Figure 3.2-4: DERIVATION OF MATERIAL GEOMETRY INDEX FOR MONOCOQUE COMPRESSION CYLINDERS modulus need be considered. Other geometries and load conditions will have more complex structural indexes. The backup document presents indexes for pressure vessels, thick-wall columns, shells, and beams.

Comparative Performance of Materials

Consideration of material cost elements in combination with the structural index permits the economic selection of materials.

It has been shown how unit cost ($/in.^{3}) of materials can be developed for aerospace applications, and how structural indexes can be derived for specific designs. Combining these parameters produces the relative cost of materials to satisfy given design requirements.

Figure 3.2-5 shows a material cost comparison for monocoque compression cylinders for a marginal transportation cost of $100/lb. The plot indicates that aluminum alloys will be superior for room-temperature application, with magnesium alloys closely competitive, followed by beryllium at higher temperatures. The basic high costs of beryllium are not repaid by its structural weight efficiency in low-temperature environments for this application.

The comparison of Figure 3.2-5 is repeated in Figure 3.2-6, but for a transportation margin of $1000/lb. There is a premium on light weight, and beryllium dominates the material selection. Magnesium alloys are the next most efficient, followed by aluminum.

A number of such comparisons are presented in the backup document (D2-114116-2).

Future Cost Improvements

Materials that are in early phases of development (e.g., composites) can be expected to show cost improvements that will affect cost selections.

The history of material developments shows an initial high purchase and fabrication cost followed by cost reductions. High costs arise from

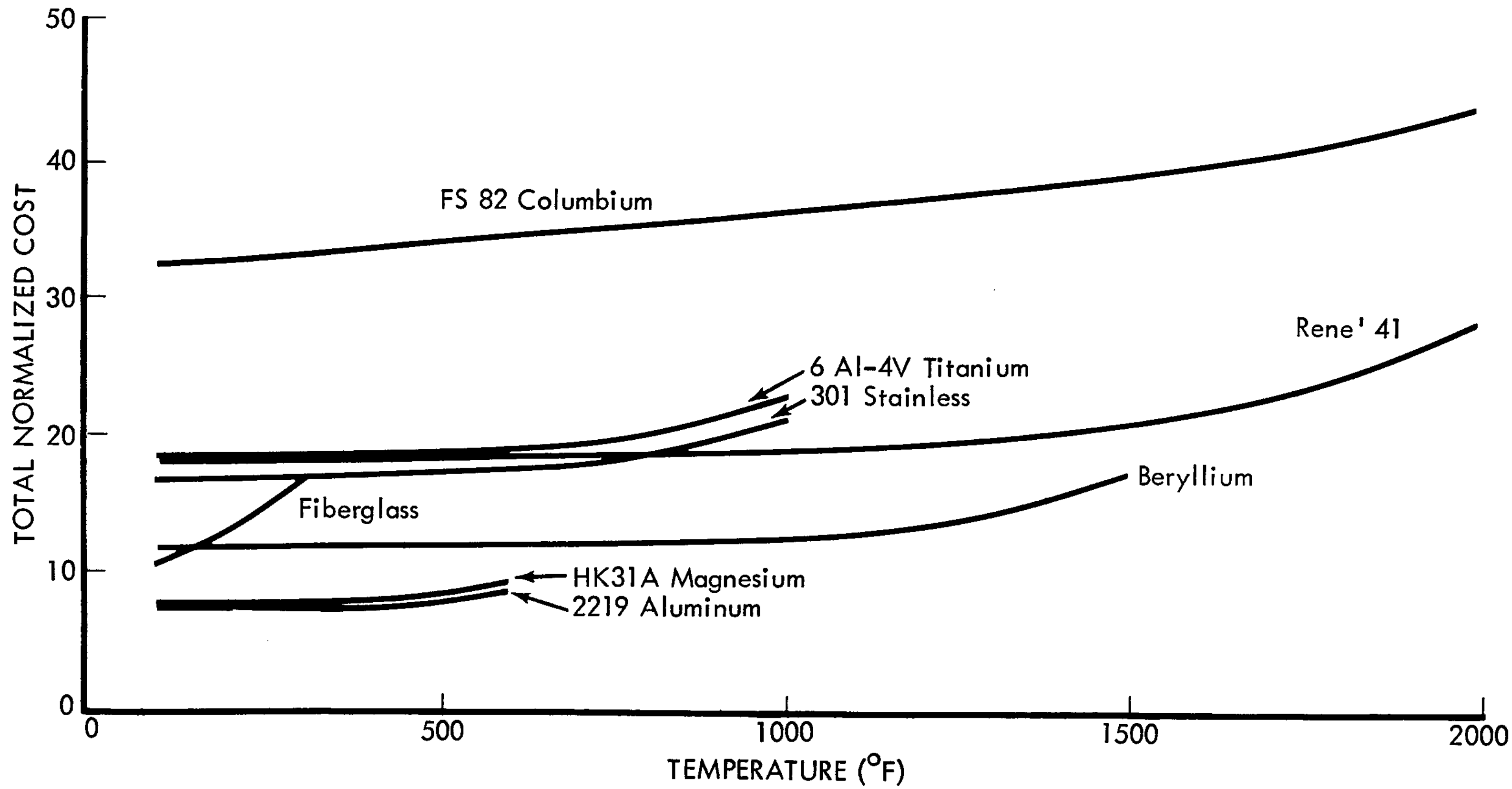


Figure 3.2-5: MATERIAL EFFICIENCY — MONOCOQUE COMPRESSION CYLINDERS
Transportation = \$100/lb

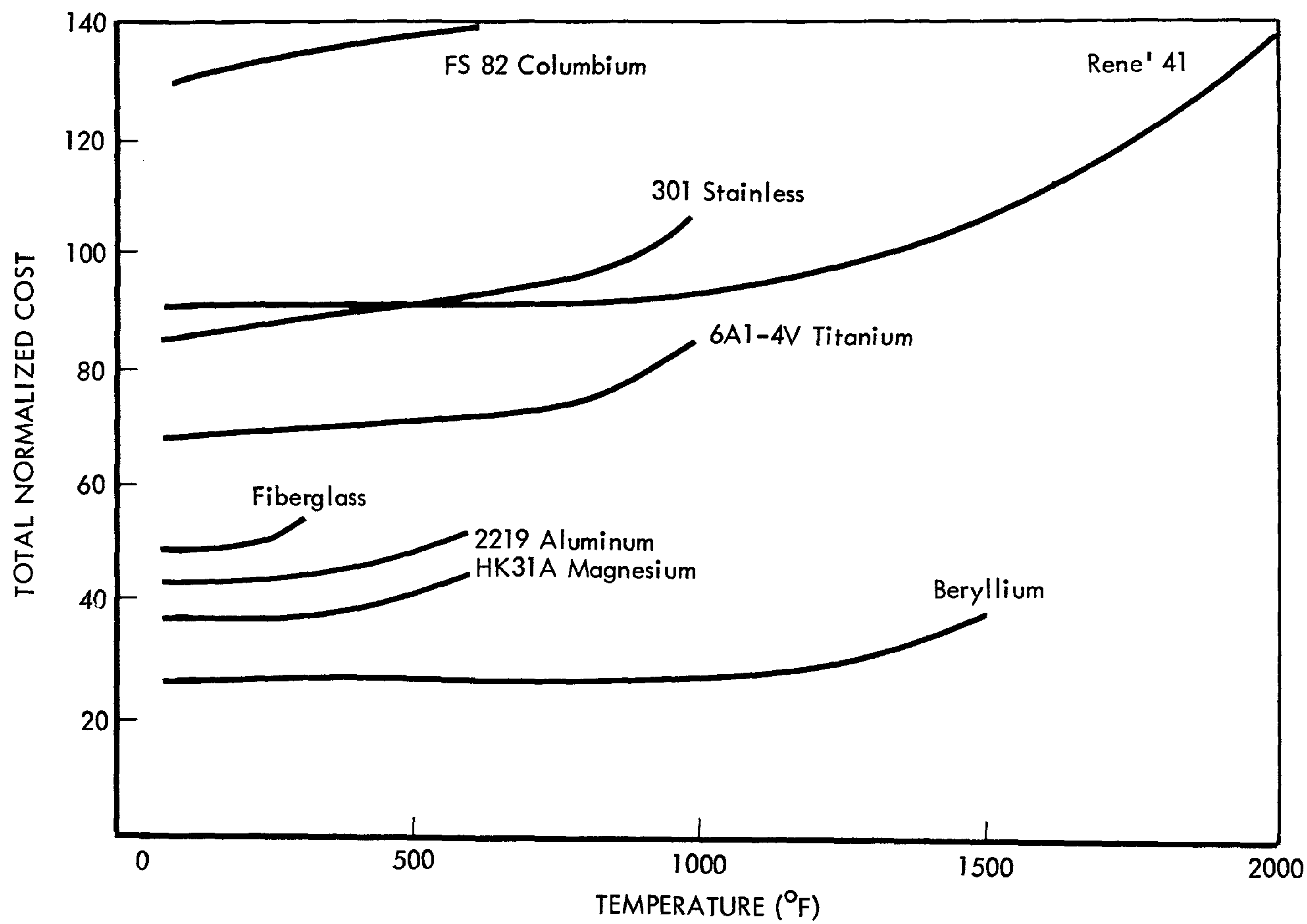


Figure 3.2-6: MATERIAL EFFICIENCY — MONOCOQUE COMPRESSION CYLINDERS
Transportation = $1000/lb

scarcity and lack of familiarity, and are naturally reduced as new production processes increase production rates and fabrication methods are adapted to material peculiarities.

Figure 3.2-7 shows the history and trends of raw material costs for high-strength whiskers and filaments---probably the highest-cost structural materials ever used. All of the materials show downward trends that can be expected to continue for some time. Because they are new, these materials require a different technique of cost comparison.

Exchange Curves for Composites

Exchange curves of raw material and fabrication costs for composites can be used to evaluate the potential of these materials in specific applications.

Exchange curves showing all combinations of raw material cost and fabrication cost at which a composite material can compete economically with a conventional material provide a powerful approach to evaluating the future of composites. Such curves are drawn by considering specific applications of structural geometry and transportation cost, and evaluating, with the previously described material costing techniques, the cost levels at which composites produce the same total cost as a conventional material. The merits of composites in various applications can then be identified. Furthermore, if there is some knowledge of the difficulties in fabricating these materials, value judgments of the raw material cost levels at which they become effective can be made.

Figure 3.2-8 compares boron-epoxy composite with aluminum at room temperature for transportation margins of \$0/lb and \$500/lb. Four structural applications are considered. Similar comparisons are made in Figure 3.2-9 for the boron-epoxy material with titanium in a 400°F environment. For a given structural application (e.g., Euler column) and transportation cost (e.g., \$500/lb), Figure 3.2-8 shows that a combination of raw material and manufacturing cost for boron-epoxy---to the left of the line (total of \$880/lb)---is cost effective compared to aluminum. Conversely, any

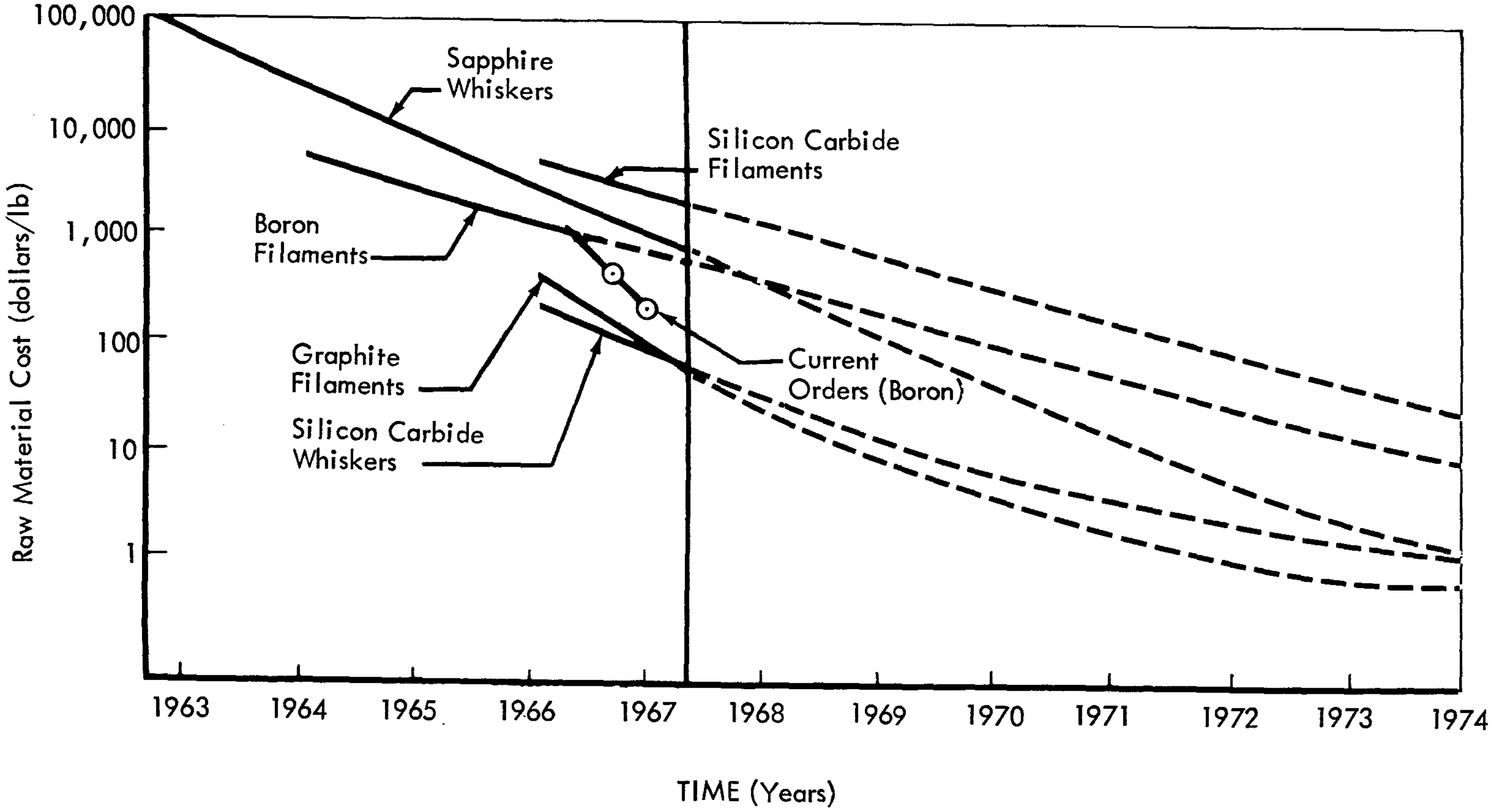


Figure 3.2-7: POTENTIAL FIBER COST IMPROVEMENTS

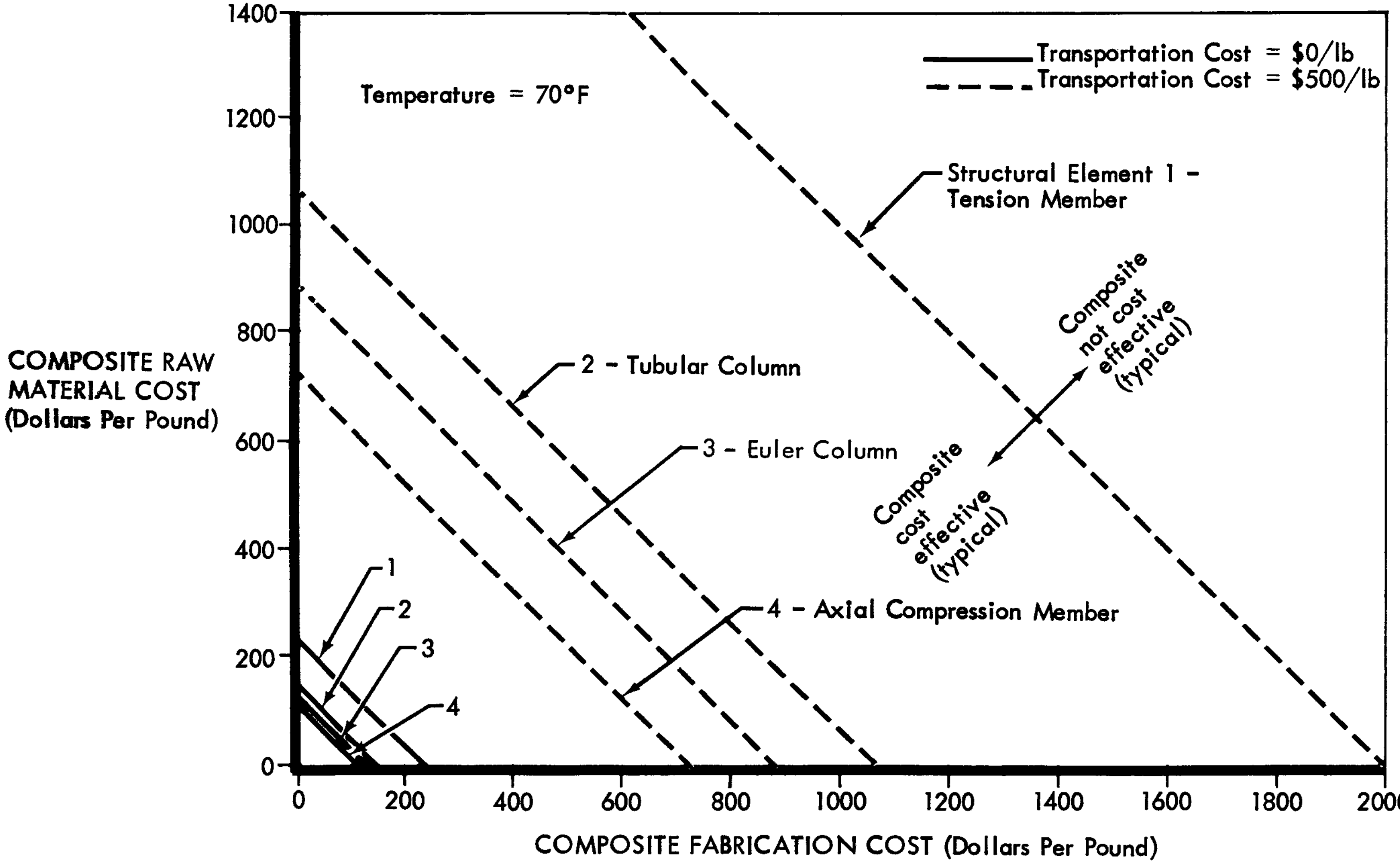


Figure 3.2-8: COMPOSITE MATERIAL BREAK-EVEN COST -- Boron-Epoxy Vs Aluminum

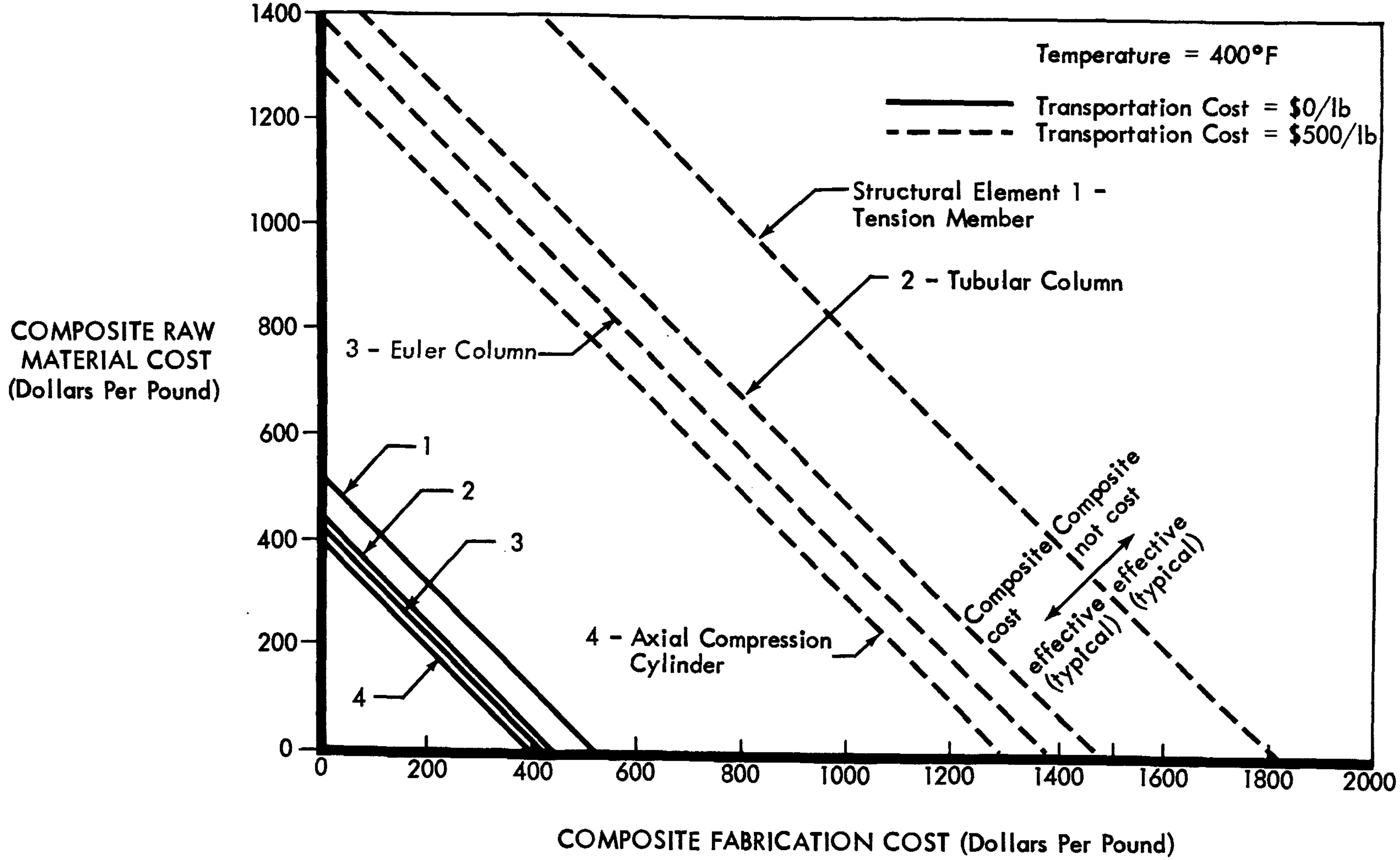


Figure 3.2-9: COMPOSITE MATERIAL BREAK-EVEN COST -- Boron-Epoxy Vs Titanium

total material cost to the right of the line is not cost effective. These two figures show the strong dependence of cost conclusions on transportation cost and component geometry.

Research Implications

The demonstrated comparisons of material effectiveness show that continuing research on advanced materials is justified only in certain specific applications.

Cost comparisons of materials show the importance of geometric application and marginal transportation cost in defining the least-cost material. An advanced material that is not cost effective in simple applications becomes cost effective for more demanding uses.

Comparisons of conventional materials shown in Figures 3.2-2, -5, and -6 indicate that their raw material costs are not large enough to affect the cost trades. However, manufacturing complexity, is a significant factor and, in combination with marginal transportation costs, produces valid optimum choices.

There is a trend in these cost trades to select the most easily fabricated materials at transportation margins below $100/lb and the least-weight materials at margins above $1000/lb.

There is further observation, not directly based on cost, but revealed in the studies of beryllium shown in the backup documentation: In ultimate compression strength design, considerations of plastic failure make the material proportional limit more important than Young's modulus as a structural index. This makes beryllium less attractive in such applications than stiffness/weight comparisons would indicate.

The composite material exchange curves (Figures 3.2-8 and -9) show that these materials, with their inherent fabrication difficulties, compete with aluminum only for high transportation margins or where their high ultimate strengths can be used fully. Comparisons with titanium at 400°F are less decisive because titanium is itself a difficult material to fabricate. However, when weight is important (transportation margin = $500/lb), the boron-epoxy composite is currently competitive with titanium.

The argument presented in Section 2.2 shows marginal transportation costs for the design of first stages and single-stage-to-orbit launch vehicles to be near $0/lb. For these applications, a general conclusion can be made from the material trades presented here that aluminum will probably remain the best launch vehicle material for some time to come.

Finally, the comparisons in this section indicate that there will always be a justification for advanced materials through the high transportation margins of high-energy missions.

3.3 CRYOGENIC CONTAINMENT CONCEPTS---LUNAR

The Problem of Environment

It is extremely difficult to achieve economical long-duration storage of cryogens in a hostile environment

Long-term storage of cryogens will become increasingly important in future space missions. Hydrogen as a propellant and as a fuel for auxiliary power applications will be used for lunar exploration missions, long-duration space stations, and planetary vehicles.

One typical application of liquid hydrogen is its use in fuel cells for a lunar exploration vehicle, such as Molab, or a lunar shelter. Typical storage requirements are 20 to 80 pounds available after a 6-month storage period.

Numerous performance studies have been conducted in this general area; the results of one have been selected to apply some of the costing principles developed in NAS7-525. The study (Reference 10), which was performed by Boeing-Seattle for NASA/MSFC under Contract NAS8-20272, developed preliminary designs for LH_2 and LOX tanks; compared them on the basis of weight, size, reliability, thermal predictability, and fabrication complexity; determined required developmental testing; and defined functional testing. The study selected is appropriate because it contained good performance data and defined testing requirements, which are important in a cost comparison.

The environment for the small hydrogen tanks studied included the following mission phases: Earth launch; Earth-Moon transit phase (110 hours); lunar shelter storage (182 Earth days); and 14 Earth days manned lunar operational period. Prelaunch and Earth-lunar transit thermal environment was assumed to be 530 and 450°R, respectively. These are external tank-surface temperatures. The tanks, on the lunar surface, were assumed to be shielded and to have an external temperature history as shown in Figure 3.3-1.

Other environmental conditions included vibration, boost loads, lunar landing loads (10.5 g vertical, or 8.5 side plus 2.5 g vertical limit). A vent pressure of 100 psia (limit) was assumed. An ultimate load factor of 1.4 was used, and yield strength was not exceeded at 110% limit load.

Concepts Available for Trade

Studies conducted under Contract NAS8-20272 provide three representative cryogenic containment designs that are suitable for comparison and have common requirements.

Three LH_2 storage systems were considered in NAS8-20272 and in the cost study summarized here.

LH_2 Storage System 1---Soft outer shell/gas-purged insulation/vapor-cooled shield.

LH_2 Storage System 2---Soft outer shell/gas-purged insulation.

LH_2 Storage System 3---Honeycomb hard outer shell/evacuated insulation/vapor-cooled shield.

Common items for all three systems are:

Insulation---0.25-mil nylon aluminized on both sides and 7-mil-thick nylon netting.

Supports---Eight fiberglass tension rods

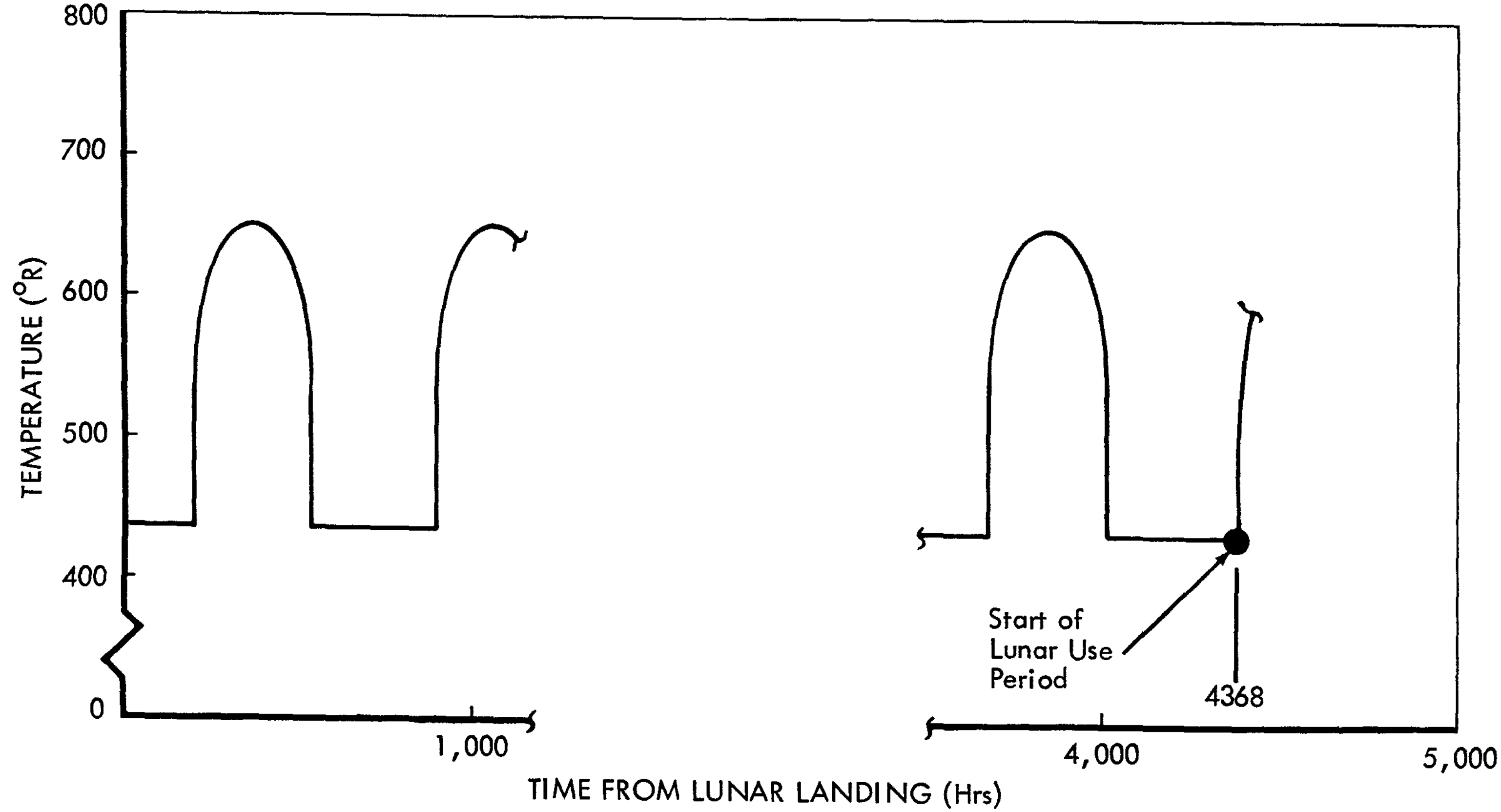


Figure 3.3-1: TANK SURFACE TEMPERATURE DURING LUNAR STORAGE

Tank Shape and Material---Spherical, 2219-T6E46 aluminum
Usable Hydrogen---80 pounds

Figure 3.3-2 shows the three insulation concepts. Considerable stress, thermal, and dynamic analysis was made after a design concept was set for each system. Manufacturing feasibility was studied against the background of Boeing fabrication experience in small cryogenic tanks.

Cost Study Approach

Cost considerations were added to the performance data from the previous study to achieve an economical rating of the three LH_2 storage concepts.

A manufacturing and cost evaluation was performed on the three LH_2 concepts. First unit costs were obtained for a 100-tank program (each concept). Cost estimates were made to the subassembly level and included both recurring and nonrecurring costs. Missing component development tests were defined and priced. It developed that the production rate was an important factor in the unit cost. A rate of four per month was assumed.

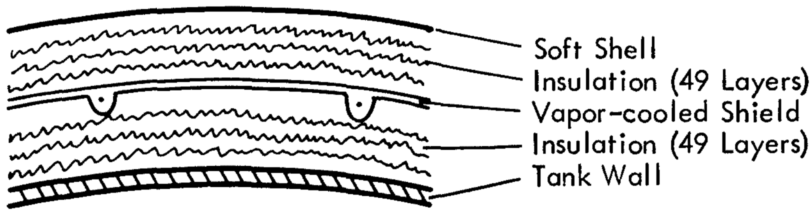
An interesting detail of costing these three concepts was the substantial insulation cost. Insulation cost was between 30 and 62% of the total cost and was strongly related to the handling of the many layers of mylar and nylon netting.

Trade Results

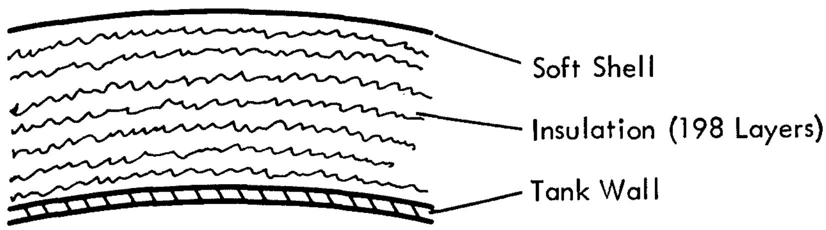
Comparison of the three LH_2 concepts shows that the superior efficiency of the soft-shell tanks more than compensates for their more complex development.

Figure 3.3-3 is a SCOT plot for the three concepts showing a cost effectiveness crossover between Concepts 1 and 2 at $600/lb marginal transportation (boost) cost. Concept 2 is more cost effective at lower boost cost, Concept 1 at higher than $600/lb. Concept 3 (hard outer shell) is never cost effective. Figure 3.3-3 makes the comparison on the basis of

CONCEPT 1



CONCEPT 2



CONCEPT 3

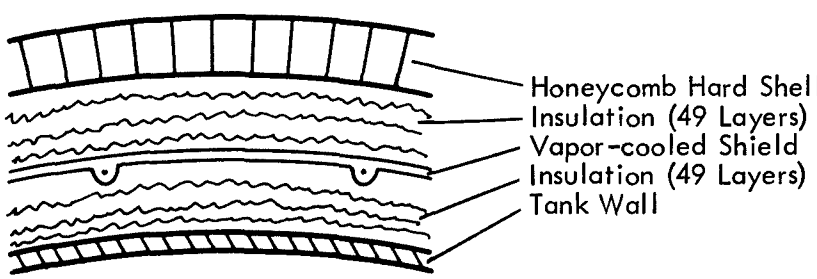


Figure 3.3-2: CRYOGENIC TANKAGE CONCEPT COMPARISON

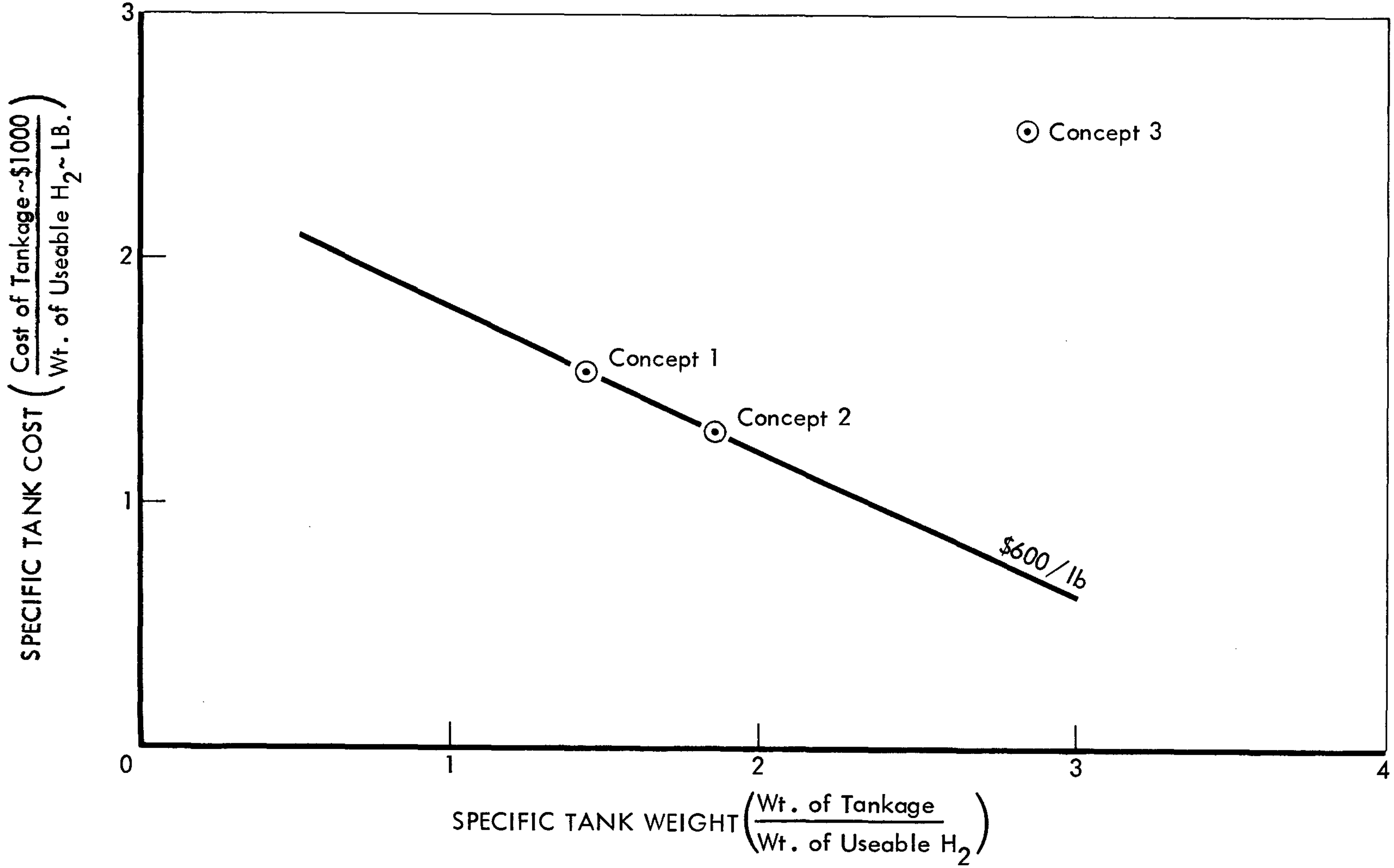


Figure 3.3-3: CRYOGENIC TANKAGE CONCEPT COMPARISON
100 Unit Program Average Cost

a 100-tank average cost. Another comparison on the basis of first-unit cost produces essentially an identical result, a $660/lb cost effectiveness crossover.

Note that the ordinate and abscissa of the figure are somewhat different from the usual SCOT plot. The normalization of cost and weight to weight of usable hydrogen was necessary to reflect that three actual designs were analyzed and costed. The three tanks were found to have amounts of LH_2 after 6 months different than the planned 80 pounds. Another design iteration would have been required to define tanks having exactly 80 pounds of usable LH_2.

Research Implications

Data indicate that cost effectiveness provides a good discrimination between three LH_2 storage concepts.

For this application, the hard outer shell concept (No. 3) for LH_2 storage is markedly inferior to the two soft-shell concepts. The hard outer shell concept has considerably higher weight and cost.

The data indicates that, for Earth orbital missions, development of the vapor-cooled soft-shell concept (No. 2) is not warranted. For lunar and higher-energy missions, use of the vapor-cooled concept can produce cost benefits, and research is warranted.

This study showed that the number of layers of insulation materials was a strong cost factor.

This cost study was one of the few which used synthesized costs (see Section 2.1). Approximately 3 months were needed to develop fully the cost data shown. The time taken, when compared to the return of information, does not seem justified for preliminary-design evaluations.

3.4 PRESSURE-FED LAUNCH VEHICLE STAGE MATERIALS

Potential of Pressure-Fed Launch Vehicle Stages for Cost Savings

Studies have suggested that launch vehicle costs can be reduced by use of pressure-fed stages fabricated of low-cost materials because of the elimination of sophisticated structural and mechanical components.

The use of a pressure-fed concept for propellant feed to launch vehicle engines elimates the need for elaborate pumps. Such pumps are peculiar to a given engine and are very costly, both from the development and recurring standpoint.

Pressure-fed propellants do increase the structural loads in the tanks. The resultant thicker tank walls have inherently higher stability to compression loads, require less elaborate handling precautions, and generally cost less to fabricate. The tanks required for high-pressure (approximately 300 psi) liquids and solid propellants are similar to commercial tanks fabricated for the brewery, oil, and food processing industries.

Material Problem for Pressure-Fed Launch Vehicle Tankage

To satisfy the requirements of low material cost, low fabrication cost, and high load carrying capability, a material choice comparison was made from among three steel alloys.

A minimum-weight design study had been performed at Boeing using three weldable steel alloys. The material properties of interest are listed below:

Material	Tensile Yield Strength (1000 psi)	Ultimate Tensile Strength (1000 psi)	Raw Material Price ($/lb)
HY-150	140	155	0.45
9Ni-4Co-0.25C	170	195	1.60
18Ni(200)	200	225	2.35

The above materials were considered for use in fabricating a 240-inch-diameter first-stage tank containing 1.4×10^6 lb of N_2O_4/UDMH. Tank pressures were near 350 psig (limit). Tank length was about 780 inches. The two higher-strength materials require a Y-ring at the juncture of heads, bulkhead, and cylinder; the HY-150 tank does not. The two higher strength steels were ground to 125-microinch finish on both sides because of their flaw sensitivity. The HY-150 plate was ground on one side only to facilitate tank cleaning.

The high-deposition gas-metal arc welding method can be used on the HY-150 tank, but the other two steels require the slower gas-tungsten arc method. Inspection requirements for the two higher-strength steels are greater due to their relatively small critical flaw size.

Material Trades for Equal Function

Although tensile strength is the traditional design condition for pressure vessels, the high stress levels and extensive weldments in this application require the consideration of flaw sensitivity to ensure equal design reliability.

The original study showed a substantial cost advantage, but higher weight, for the use of HY-150.

Material	Tank Weight (lb)	Cost per Unit for 10 Units ($1000)
HY-150	99,400	246
9Ni-4Co-0.25C	86,300	661
18Ni(200)	78,500	855

For tankage sized using these three materials to produce equal strength designs, the SCOT comparison is shown in Figure 3.4-1. The HY-150 and maraging steels have equal cost effectiveness for a marginal cost of $29/lb. Transportation cost analysis, early in this study, showed a first-stage transportation cost of from $40/lb to $70/lb. This analysis was erroneous and was an evaluation of total rather than marginal transportation cost (see Section 2.2). In fact, for a new launch vehicle, the

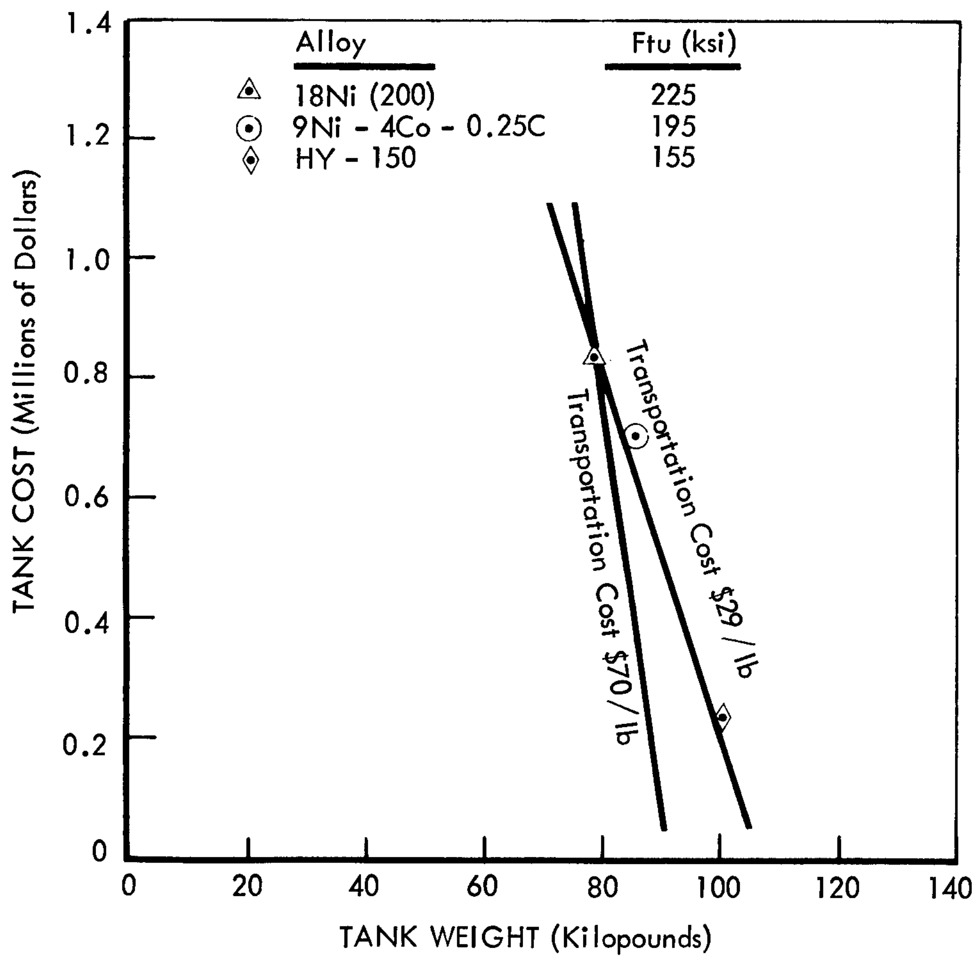


Figure 3.4-1: PRESSURE-FED TANKAGE - MATERIAL TRADES

first-stage marginal transportation cost is nearly zero, and HY-150 is clearly the cost effective material.

Because of the lack of fracture toughness inherent in the 9Ni-4Co-0.25C and the 18Ni(200) steels, tanks made of these materials will not have the same reliability as the HY-150 tank. Consequently, some of these tanks will not survive proof tests, which will increase the price of the surviving tanks. To bring the tank designs to equal reliability, stress levels must be reduced in the flaw-sensitive materials so that critical flaw size is increased to a detectable level. When this is done, the SCOT comparison shown in Figure 3.4-2 is developed. For the assumptions made, the HY-150 is cost effective for *all* values of transportation cost. Costs decrease for the flaw-sensitive materials because the increased tank gages permit design simplification. This comparison shows the importance of assuring equal reliability when design concepts are traded.

Research Implications

Correct economic selection of materials for a highly loaded design requires consideration of fracture mechanics to ensure reliable operation and dictates the use of HY-150 in the application studied.

A better understanding of fracture properties and mechanisms is indicated for candidate, highly stressed materials. Improved inspection methods and equipment are required to permit flaw detection. Careful work is required to understand the compatibility of materials and fluids contained with respect to the initiation of stress corrosion.

Lower strength, "boiler code" materials do have a proper place in economical pressure vessel design for pressure-fed liquids and solid propellants.

Early consideration is required to foresee and evaluate the total system that uses such materials. HY-150 merits specific attention for new booster tank design, especially for transportation costs below $100/lb.

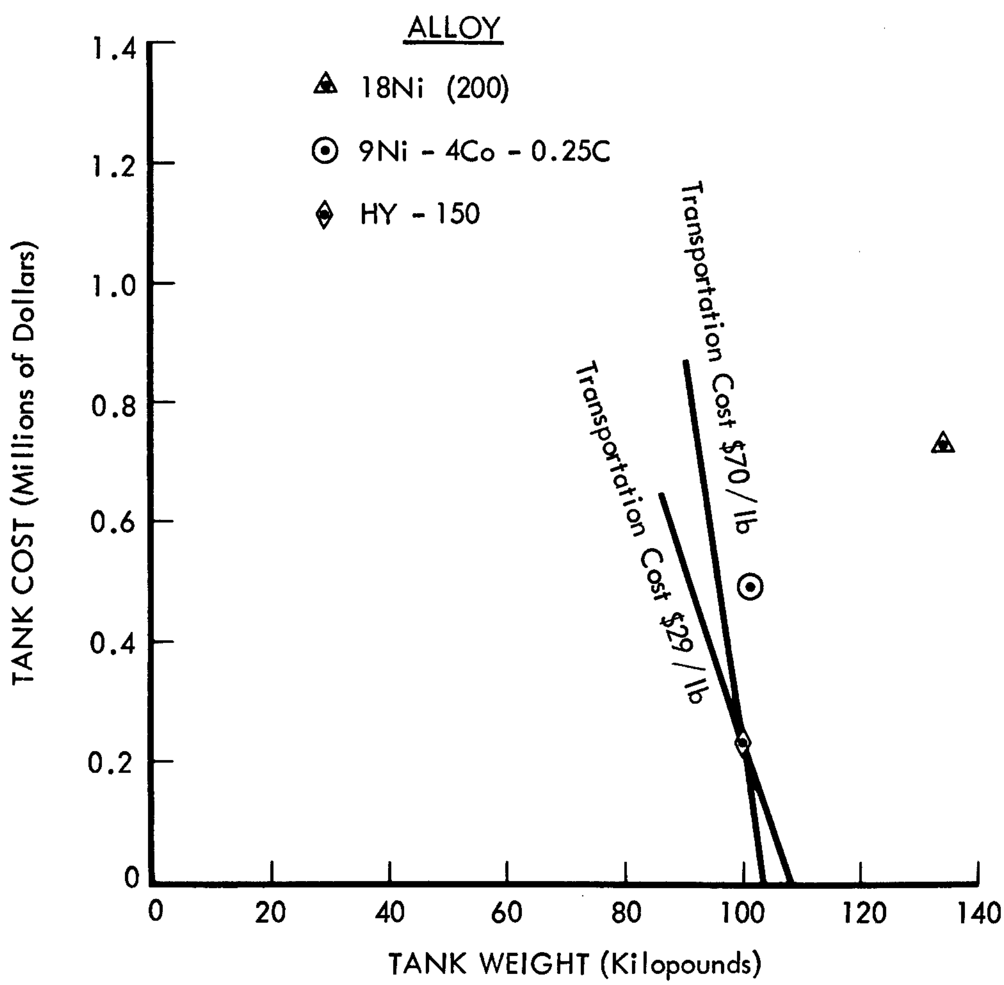


Figure 3.4-2: PRESSURE-FED TANKAGE TRADES — RELIABILITY COMPARISON

4.0 SYSTEMS STUDIES

The Role of Structure Within the System

There is a strong two-way interaction between the structural subsystem and the system as a whole.

One of the primary goals of this study effort was to relate structural research to areas where economic gain could be realized. Economic gain in what? Not just the direct cost of vehicle structure, since that is one of the least costly elements of a space program, but economic gain in those areas of the system where high costs are incurred *because* of the structural subsystem. Structure usually accounts for a large portion of a spacecraft's weight; therefore, the transportation (boost) costs are of special concern because they are an important increment of the total cost.

A conventional spacecraft weight statement is usually broken down by subsystem. The structure weight is the sum of that separate, load-carrying assembly, called primary structure; and those distinct brackets, shields, etc., called secondary structure. The other subsystems are full of structure; at least they have many structural problems. Turbine blades creep, seals cold-flow, bearings gall, and so on. A better understanding of other subsystems by structures engineers is necessary to properly reflect the cost-weight balance and, of course, the functional reliability.

Finally, the high nonrecurring costs of integrating other subsystems (such as environmental control, electrical power, and crew support) with a vehicle structure are often overlooked. Frequently, these integration costs are found applied to the structure, since they represent assembly and installation operations on structure. Analysis usually shows that such integration costs are peculiar to a given structural arrangement and would be incurred again for another arrangement.

Application of Cost Techniques to Systems

Economic tools are available to apply minimum cost as a goal for system planning.

Section 2.0 presents some tools for economic analysis. Concept selection technique (Section 2.3) and configuration by economic analysis (Section 2.5) are specifically system analysis methods. SCOT (Section 2.4) is applicable at the part, subsystem, and system level. Cost technology (Section 2.1) and transportation costs (Section 2.2) are basic to any cost analysis.

The methods described in Section 2.0 are not a complete list, but they are those that have been used during this study. Other methods and different applications of those listed should be developed.

Figure 4.0-1 depicts schematically the application of cost tools to systems problems and the consequent dropout of structural research implications.

Maximum Performance and Minimum Cost

The design decisions that result from a minimum cost goal are generally different from those that result from a maximum performance goal.

A design philosophy has come into the aerospace field after long use in aeronautical design. In aeronautical engineering, the relatively low cost of structure and the high cost of excess weight led to "boundary value" solutions of economic optimization---the least-weight design yields the least-cost system. Launch vehicle limitations made the minimum-weight approach mandatory until recently.

The advent of larger launch vehicles, such as in the Titan and Saturn families, has made possible a look at system economics by the matching of payload and launch vehicle. Future, more expensive, developments will have to consider system economics even more.

Figure 4.0-2 illustrates the difference between a cost and performance optimized design for a two-stage-to-orbit launch vehicle. Performance optimization is assumed to be minimum weight at launch. Propellants are LOX/RP-1 in the first stage and LOX/LH_2 in the second stage. Launch

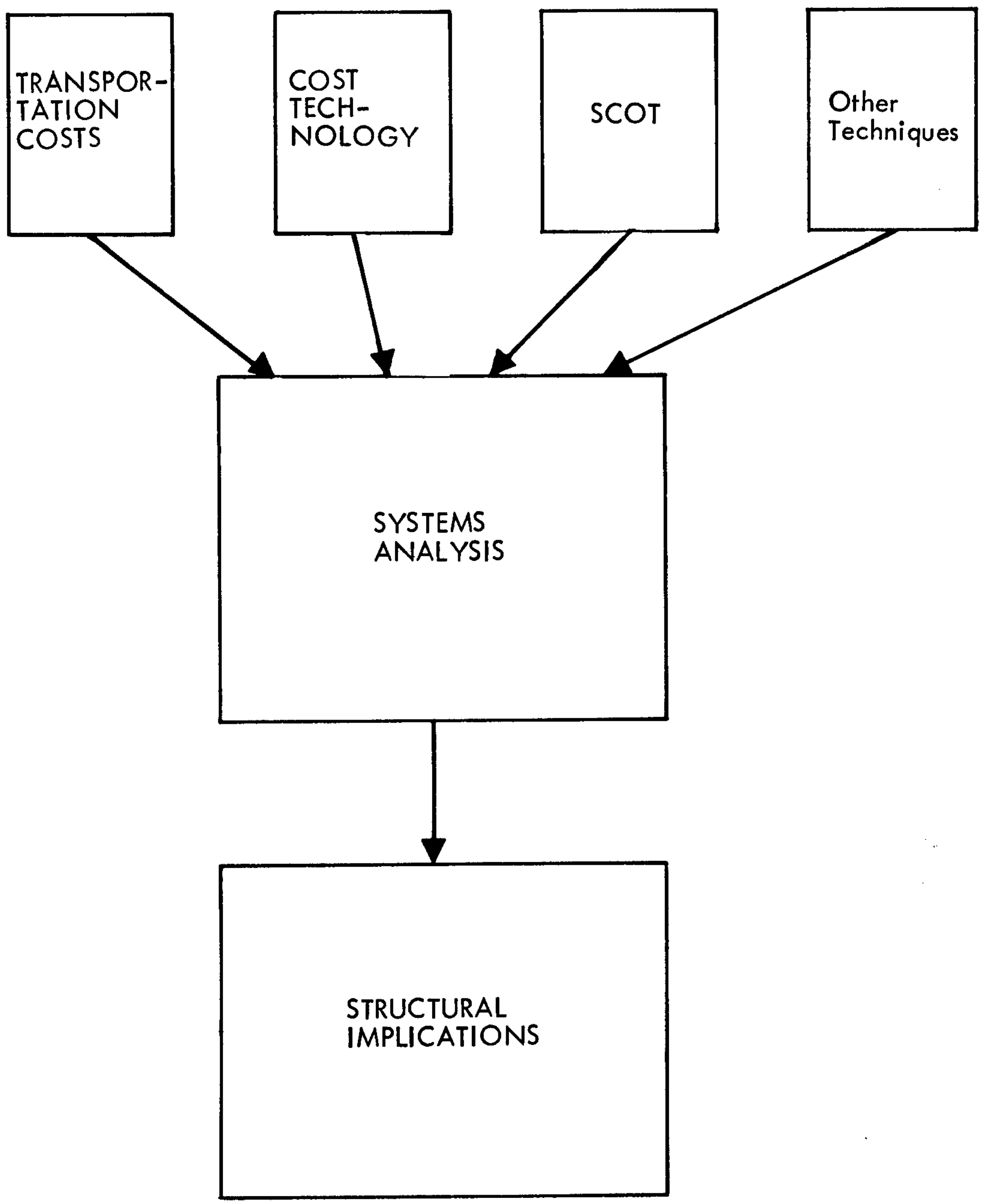


Figure 4.0-1: THE SYSTEMS COST APPROACH TO STRUCTURAL RESEARCH

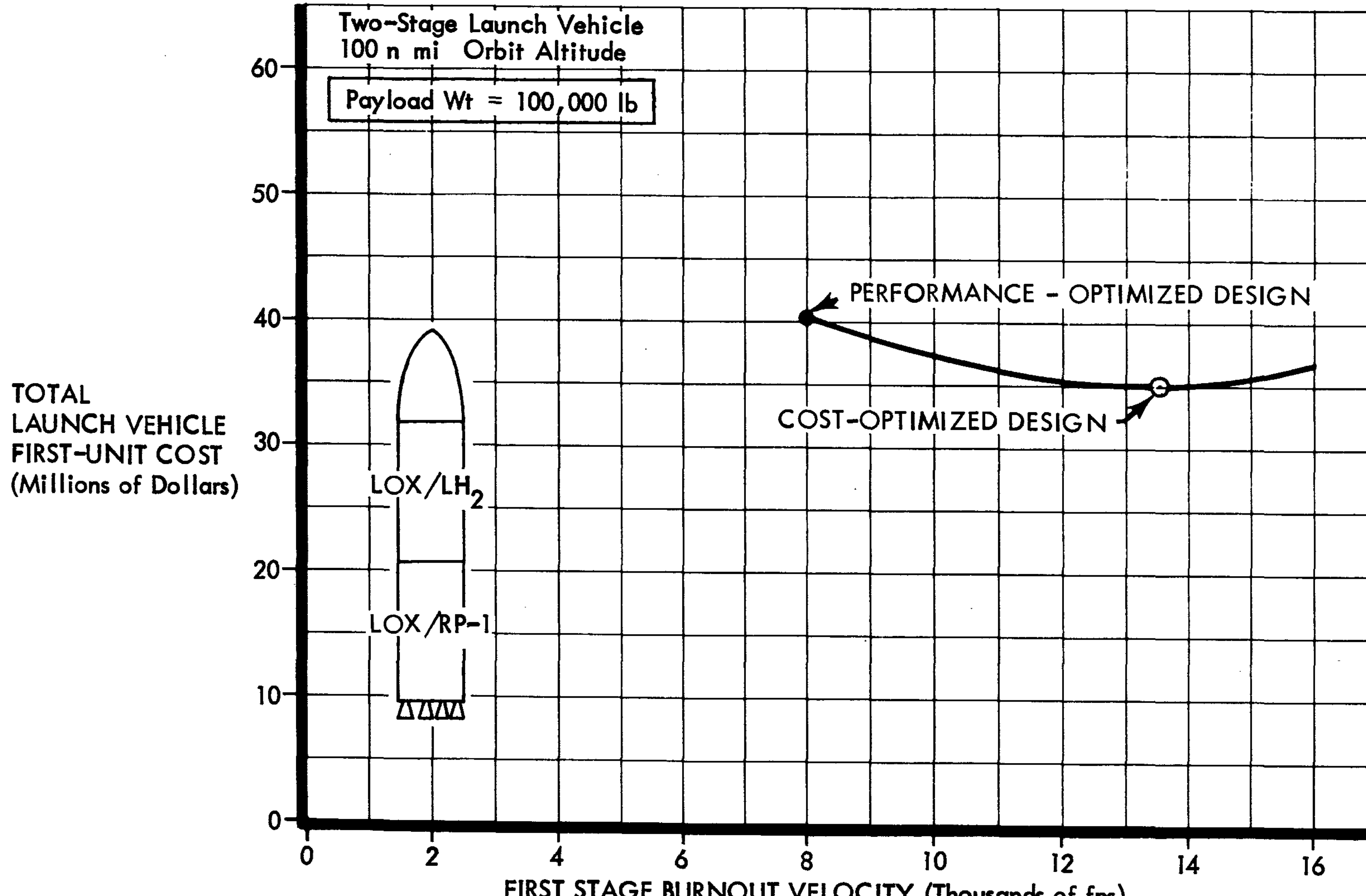


Figure 4.0-2: LOX/RP-1 - LOX/LH_2 LAUNCH VEHICLE STAGING VELOCITY TRADE

vehicle first-unit recurring cost is plotted versus burnout velocity of the first stage, for a payload of 100,000 pounds. It can be seen that the cost-optimized design stages at a considerably higher velocity and is significantly lower in cost.

Systems Studies

System studies led to certain structural conclusions.

This section summarizes five system studies and their structural research implications. The five studies are:

1) Selection of entry vehicle configuration;
2) Space mission module commonality;
3) A "new start" launch vehicle;
4) Earth launch vehicle comparison for manned Mars mission;
5) Cost sensitivity analysis for manned Mars mission.

Numerous other studies are significant, and it is hoped that additional work can be done along these lines. The yield in identification and justification of research appears to warrant the effort.

4.1 SELECTION OF ENTRY VEHICLE CONFIGURATION

Importance of Entry Vehicles in the Space Program

Entry into Earth's atmosphere is a requirement for any program that involves man-in-space or the reuse of space hardware.

A continuing emphasis on entry vehicle design is appropriate because of the severity of the environment and the extremely high cost and vital nature of this phase of space operations. It is important that entry vehicle configuration be understood in the light of total system cost so that proper emphasis can be placed on the required research.

The study summarized in this section demonstrates a method for entry vehicle configuration selection for a given set of missions, and various mixes of those missions, where system cost is used as the criterion. Also considered were separate vehicles for each mission versus multimission vehicles, entry vehicle reuse, and the effect of launch vehicle transportation cost on configuration selection.

The three missions selected for this study and their assumed requirements are summarized below.

			Entry Vehicle Size		
Mission	Equivalent Size (No. of Men)	Reqd Crew	Cargo (Payload) Wt (lb)	Lateral Range (n mi)	Maneuver ΔV (fps)
Satellite Inspection	6	2	1100	600	5000
Logistics	12	6	1700	200	1000
Recon---Once Around	2	1	300	1200	0

Additional detail may be found in the backup document, D2-114116-2.

The Lateral Range Trade

Entry vehicle configuration, characterized by hypersonic lift-to-drag ratio (Figure 4.1-1), is the subject of a trade when footprint or entry corridor requirements exist, because these requirements can be satisfied either aerodynamically or by propulsion.

Figure 4.1-2 shows a typical plot of boosted weight versus hypersonic L/D for the specified conditions. The particular requirements stated produce a sharply defined least-weight point at L/D = 1. Configurations having less L/D require lateral maneuver propulsion, which increases their boosted weight. Entry vehicles having higher L/D weigh more and have excess lateral range capability.

Other mission requirements produce different boosted weight relationships. It is essential that these requirements be carefully defined because they have a strong influence on configuration selection.

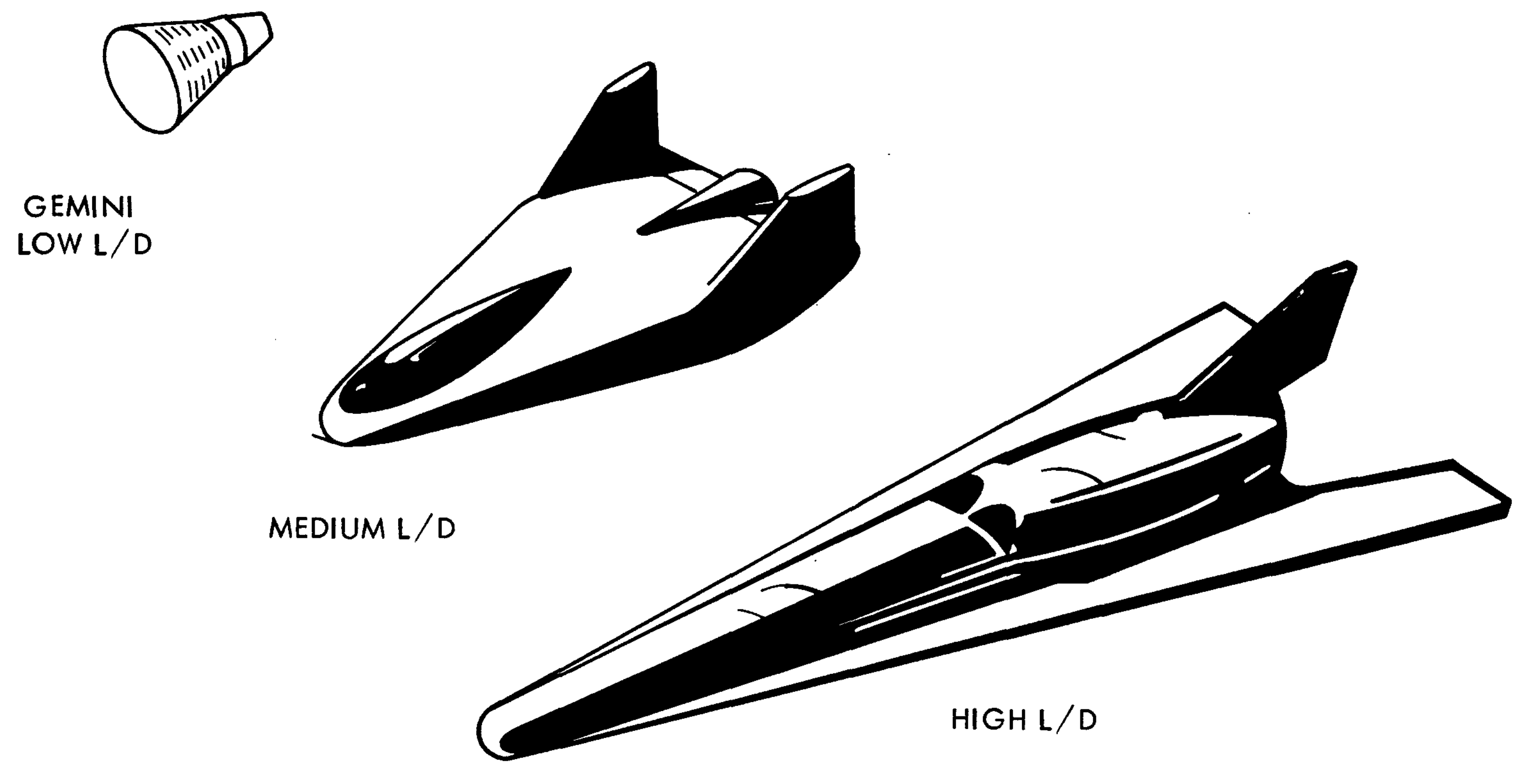


Figure 4.1-1: ENTRY VEHICLE CONFIGURATIONS

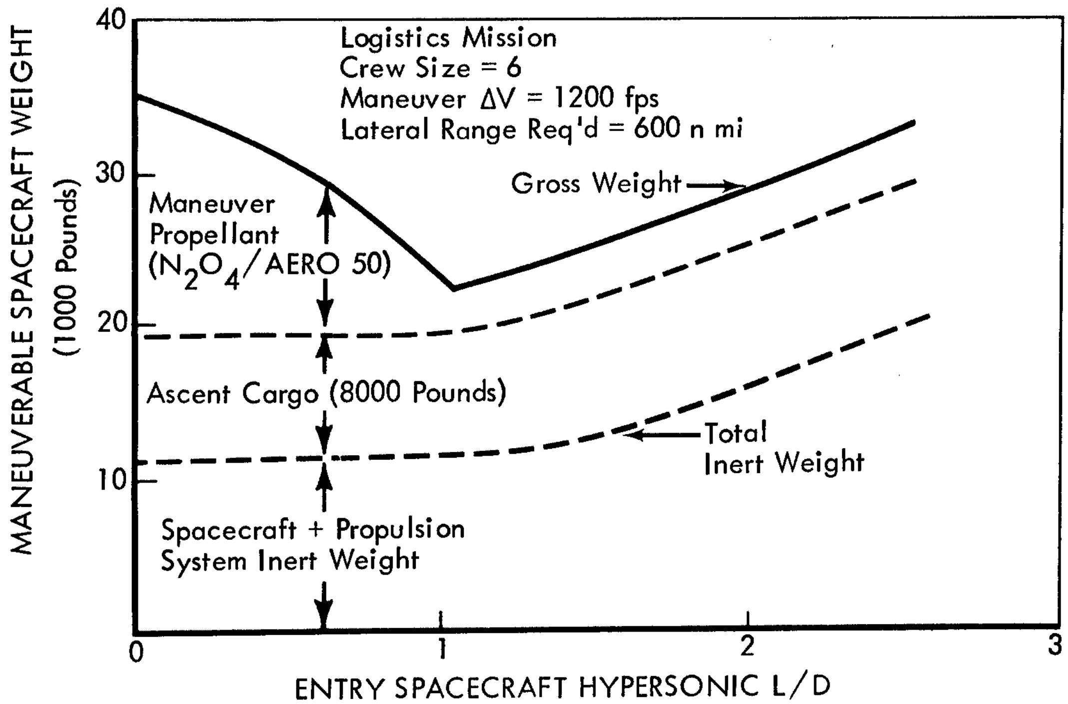


Figure 4.1-2: PROPULSION - L/D TRADES FOR LATERAL RANGE

How Cost Considerations Affect the Trade

Although range and corridor are achieved with lower weight aerodynamically than propulsively, the lower cost of propulsive systems presents the opportunity for trade.

Figure 4.1-2 showed the difference in boosted weight attendant to entry vehicle configuration. The evaluation of that weight in terms of cost can present a quite different picture, since entry vehicle and propulsion stage costs are substantially different.

Figure 4.1-3 shows the first-unit recurring costs for entry vehicles and expendable propulsion stages. Nonrecurring costs (R&D) were assumed to be $\$1 \times 10^9$ for a propulsion stage and a single mission expendable entry vehicle, and $\$1.5 \times 10^9$ for a multimission expendable entry vehicle.

Study Results

Minimizing program cost results in the selection of entry vehicles having hypersonic L/D's between 0 and 1.5, depending on mission mix and vehicle commonality.

The entry vehicle configuration study results are shown in Figure 4.1-4. The costs displayed are for a total program and include costs for boosting, maneuver propulsion stage, entry vehicle and adapter, booster escape and retro systems, payload, recovery, and tracking. Both recurring and nonrecurring costs are included. A total program of 90 missions was assumed and a 90% learning curve applied to all recurring costs.

The data in Figure 4.1-4 are for an assumed boost cost of $500/lb in orbit. The study also considered boost costs of $1000 and $1500/lb in orbit.

The following set of conclusions can be drawn from this study:

1) For this set of missions, the total program costs are relatively insensitive to the entry vehicle L/D;
2) The "best" L/D can be influenced by mission mix as well as the types of missions;
3) The least-weight system is not the least-cost system;

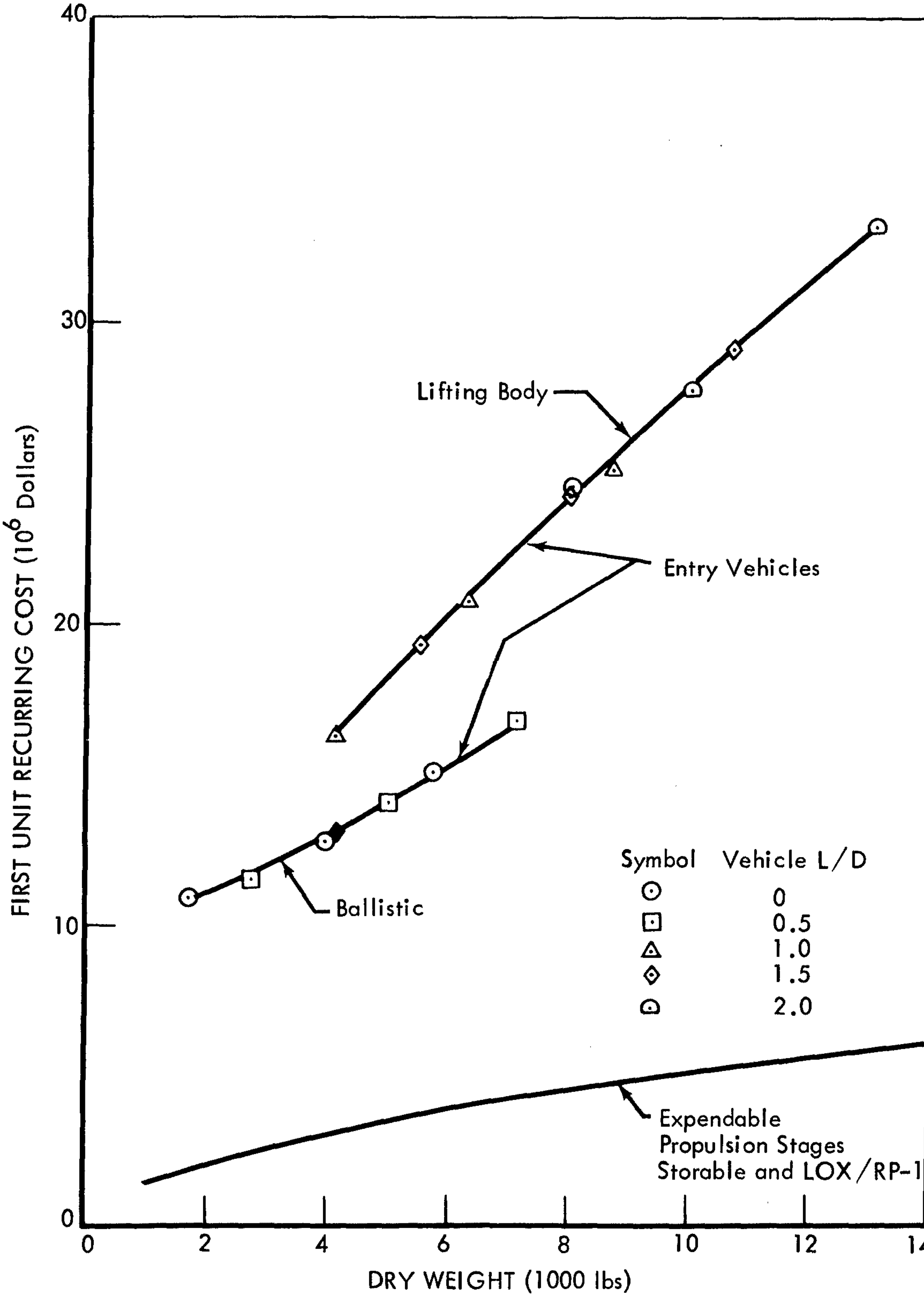


Figure 4.1-3: FIRST UNIT COSTS VERSUS WEIGHT

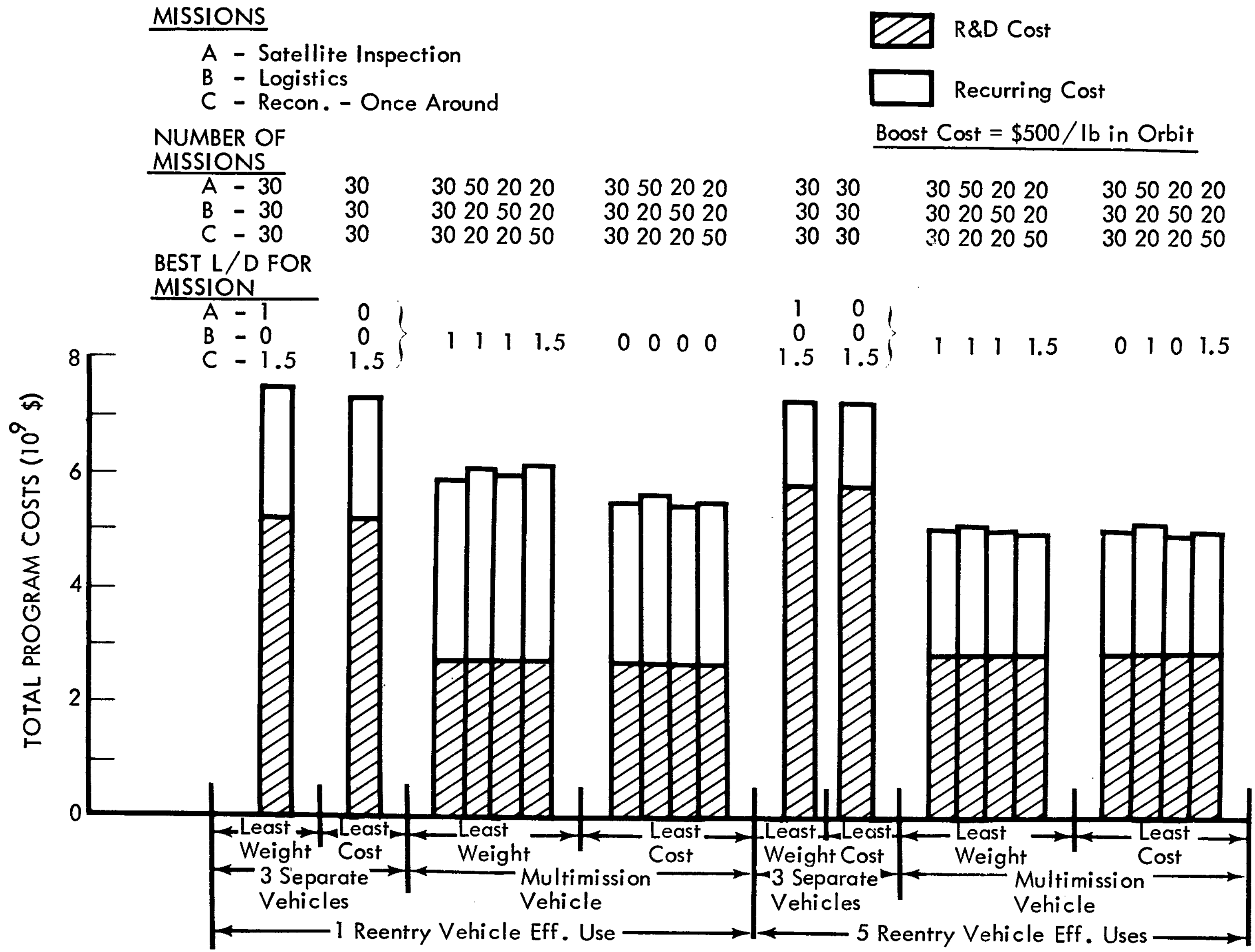


Figure 4.1-4: ENTRY VEHICLE L/D - MISSION COST TRADES

4) The increase in recurring costs for a multimission vehicle is more than compensated by its reduced R&D cost per flight;

5) Total program cost reduction for reusable entry vehicles (five effective uses) is significant, but not astounding;

6) Increased boost costs have little effect on the multimission vehicle L/D selection for entry vehicles having one effective use, but significant effect on entry vehicles with five effective uses;

7) The effect of changes in R&D costs with entry vehicle L/D should be investigated.

Research Implications

The entry vehicle configuration study has pointed to certain structural research implications in the areas of vehicle L/D, vehicle reuse, vehicle multimission use, and the effect of boost cost.

Mission requirements for lateral range are all-important in defining an entry vehicle configuration. The least-boosted-weight system consists of an entry vehicle with inherent lateral range capability, rather than a combination of an entry vehicle and a propulsion stage. Where an available booster limits the thrown weight, aerodynamic attainment of lateral range is the only recourse. Cost effective design calls for use of a medium to low L/D vehicle with an appropriate propulsion stage. Future mission requirements are not completely clear, but it appears that entry vehicle research should be concentrated in the low to medium L/D range.

Continued work should be done on devising cheaper entry vehicles and concepts for which per-flight maintenance is 5% or less of the first cost.

4.2 SPACE MISSION MODULE COMMONALITY

Need for the Space Mission Module

The development plan for the SMM deserves special consideration because the SMM is a prime requirement for future man-in-space programs, and because it is the single most expensive hardware development in the foreseeable future.

The SMM is the mission element that provides for the safety and well-being of astronauts on a long-duration space mission. It may or may not have an integrated experiment function. When long-duration manned space flight does occur, a qualified SMM will be required.

Recent Boeing studies show that the SMM will cost between $3 billion and $6 billion over the development, test, and operation cycle out to a Mars landing mission. An expenditure this large deserves special attention to economic alternates.

Differences in Requirements

Although the basic SMM requirement---to keep man healthy for long durations in space---is independent of mission, there are varying mission requirements (including mission duration, number of men, and heliocentric radius) that indicate different designs to minimize weight for individual missions.

Figure 4.2-1 displays four-man and six-man SMM weights as a function of mission time for Mars flyby and capture missions, an Earth orbit (synchronous) mission, and Venus missions. Also shown are the expended weights. Note the assumptions listed on the figure.

The weight spread for a given mission time is due to the difference in electrical power system weight as a function of the distance from the Sun.

Alternate Development Concepts

There are three basic alternatives to SMM development from which a minimum cost development can be chosen:

1) *Full optimization for individual missions;*
2) *Optimized structure for individual missions with common subsystems;*
3) *A multimission vehicle of completely common design.*

The basic trade between alternate SMM concepts involves the savings in a single development as balanced by the requirement to accelerate the resultant heavier, off-optimum vehicle.

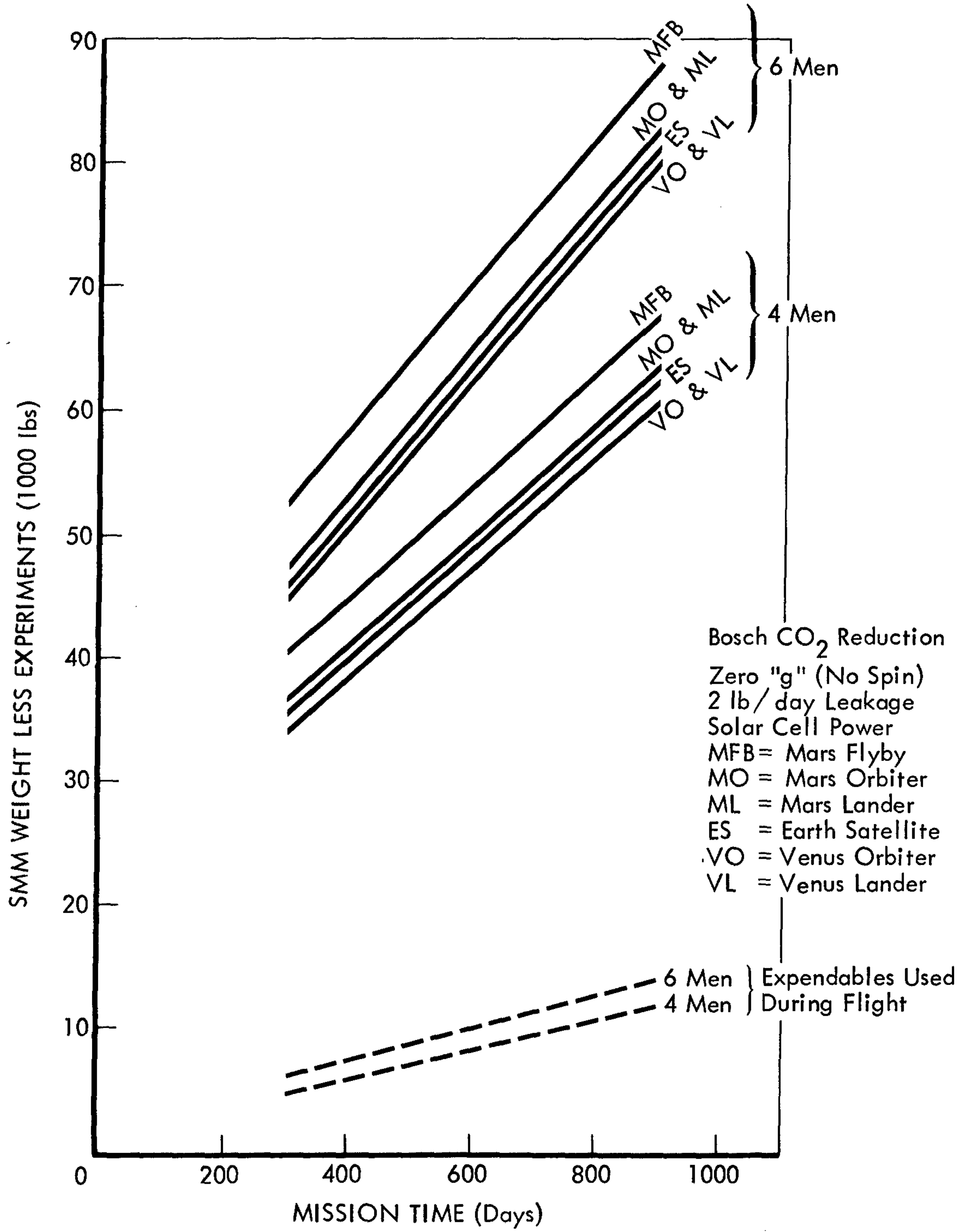


Figure 4.2-1: SPACE MISSION MODULE WEIGHTS

The mission mix against which the three SMM development concepts were compared involved five low-Earth-orbit missions as a national space station (NSS), two Venus flyby missions (VFM), and five Mars lander missions (MLM). A six-man crew was assumed for all missions together with a time period from 1970 to 1980. Saturn V was assumed as the Earth launch vehicle, with nuclear space propulsion modules added for Mars capture and escape.

The types of subsystems utilized in the costing exercise are briefly summarized below.

Mission	Structure	Environ Control	Comm & Data Mgt	Elec Power	Guidance Stab Control	Crew Support
(⊕) NSS	New	Sabatier mol. sieve	Mod Apollo/low data rate	8-mil solar cell	Basic Apollo w/o guidance	Vapor compression
(♀) VFM	New	Same	Mod Apollo/plus Voyager-type antenna & large amplifiers	4-mil solar cell	Mod basic Apollo	Same
(♂) MLM	New	Same	Same as VFM with larger amplifiers	Cad Sulf Solar Cells	Mod basic Apollo	Same
COMMON (Alternate 3)	NSS	Same	MLM	NSS	MLM	Same

Figure 4.2-2 is a schematic of the three SMM development concepts. Alternate 1 considers that each of the three basic mission modules is developed by different subcontractors and prime contractors. A derivative of Alternate 1 could consider a degree of technology drawn from preceding developments. It is felt, however, that the three alternates chosen represent the range of ways in which an SMM development would proceed.

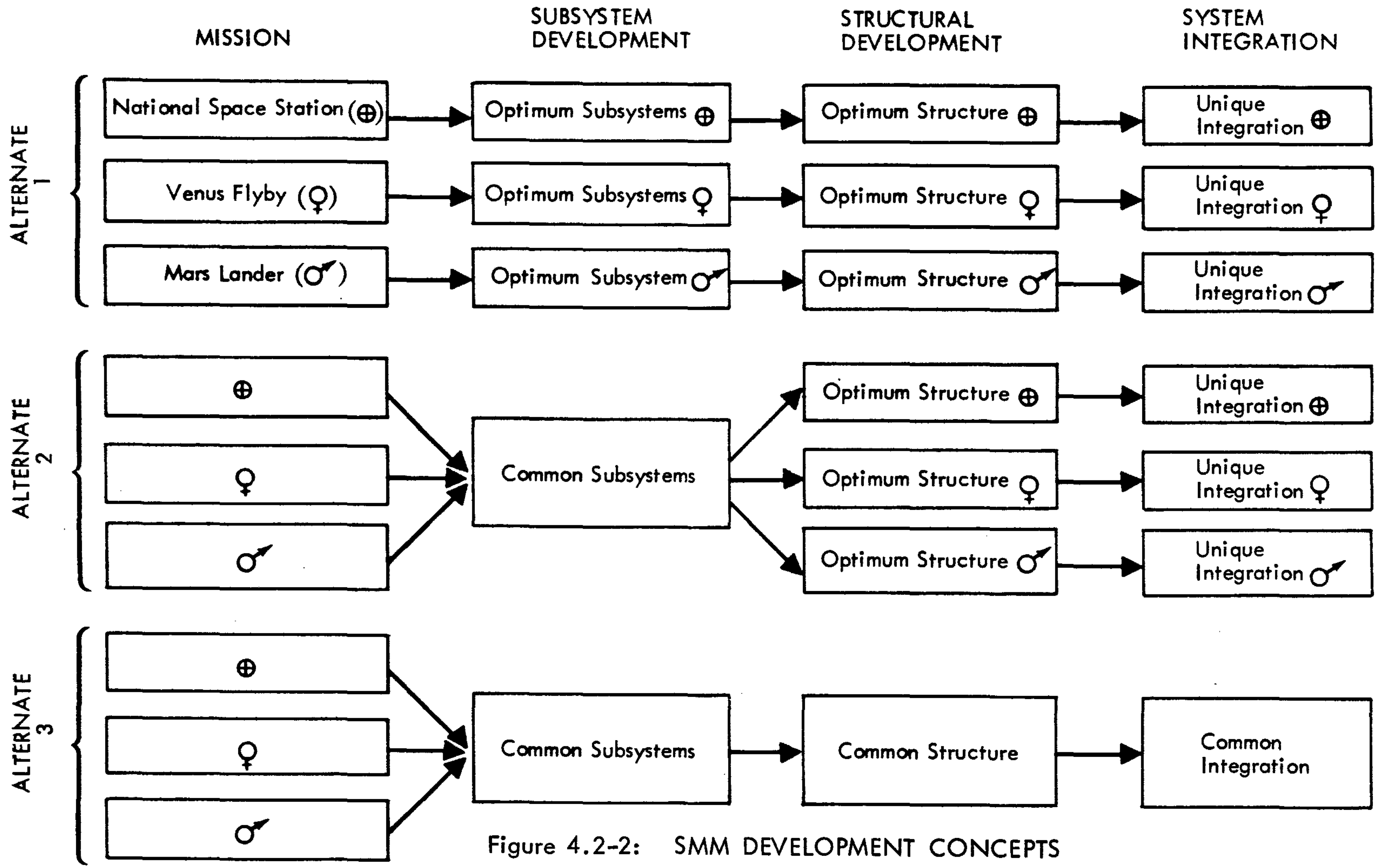


Figure 4.2-2: SMM DEVELOPMENT CONCEPTS

Cost Elements

Cost elements required to differentiate among the three development concepts are, in matrix form, subsystems in the vertical array and basic R&D, management and integration, hardware, and transportation in the horizontal array (Figure 4.2-3).

Total program cost is to be used to evaluate the three development concepts. It is essential that all costs be considered and applied fairly to each alternate.

Basic R&D involves all costs for the design, development, manufacturing, and testing of an item prior to first flight article integration. This category collects the costs of all ground test units.

Management and integration includes those costs for integrating and assembling subsystems into a system. Also included is the system-level checkout and acceptance of all subsystems on the assembled spacecraft. Ground support equipment, launch site support, training, and simulators are also included in the management and integration cost element. Finally, this category includes the costs of integrating the SMM with other flight units. Generally, the costs in the management and integration cost element cannot be allocated by subsystem.

The hardware cost element includes spares.

Transportation costs entail propulsion hardware costs, launch and flight operation, recovery, integration, and management. In addition, R&D costs are included for the space propulsion modules in the Mars lander mission.

Study Results

Results of the study show that a common design (Alternate 3) has an economic advantage despite the high marginal transportation costs for planetary mission, and that separate structural developments with common subsystems (Alternate 2) lead to higher costs than totally unique system developments (Alternate 1).

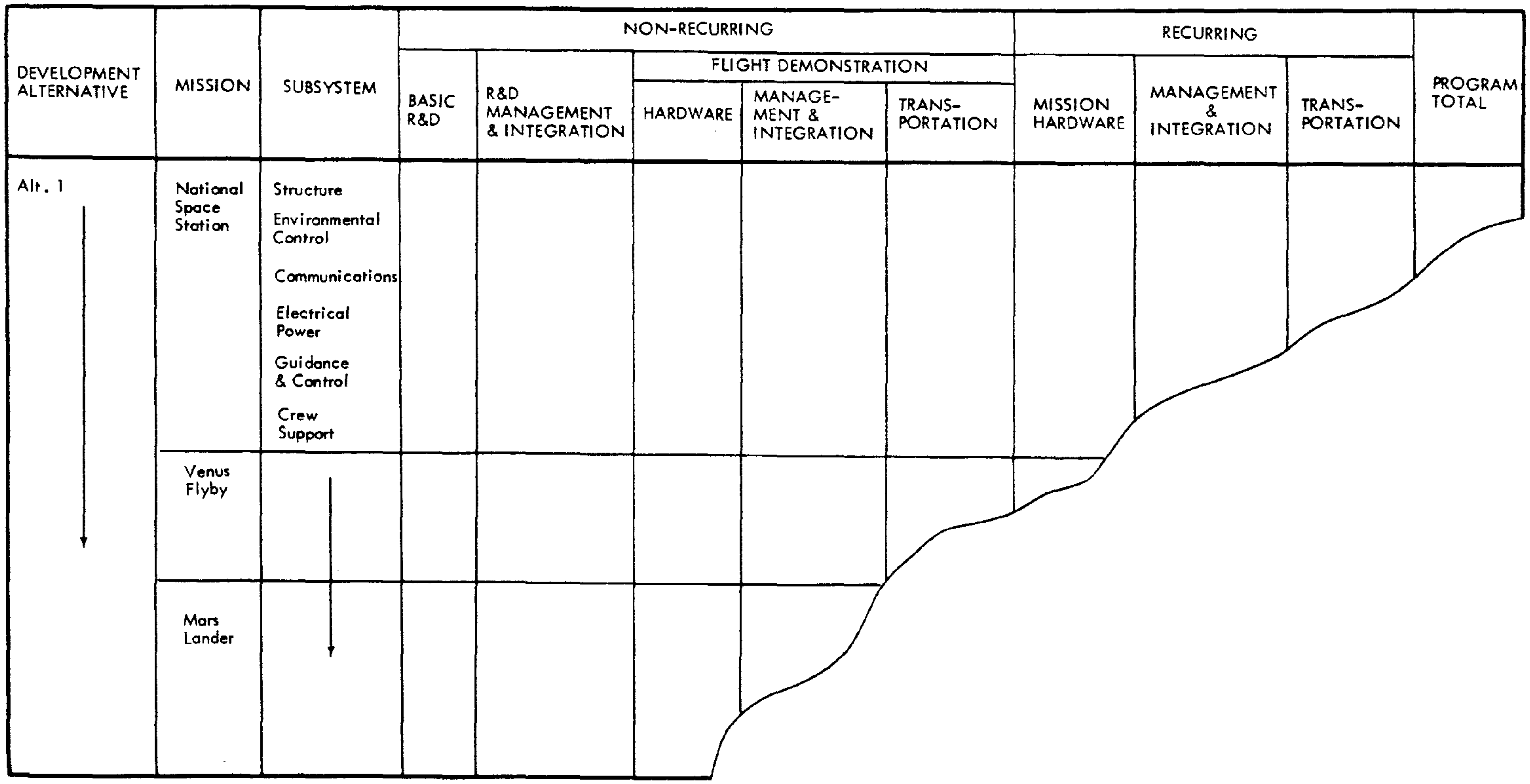


Figure 4.2-3: SMM COST ELEMENT MATRIX

Figure 4.2-4 shows cost comparisons among the three SMM development alternates. The shaded-bar comparison excludes transportation costs; the open bars include transportation.

Excluding transportation costs, Alternate 3 is indicated to be the least expensive approach, followed by Alternates 2 and 1. SMM development Alternate 3 (single common SMM) has a cost that is \$2.6 billion or 30% less than Alternate 1, and approximately \$1.4 billion or 20% less than Alternate 2.

Including transportation costs tends to equalize all alternates. Transportation represents 68 to 78% of the total program costs. Transportation costs assumed for this SMM study were \$1400/lb for the NSS, \$9350/lb for the Venus flyby mission, and \$73,270/lb for the Mars lander mission. Figure 4.2-4 was developed using this data and shows Alternate 3 slightly less costly than the other two alternates, but all three within a 7% spread.

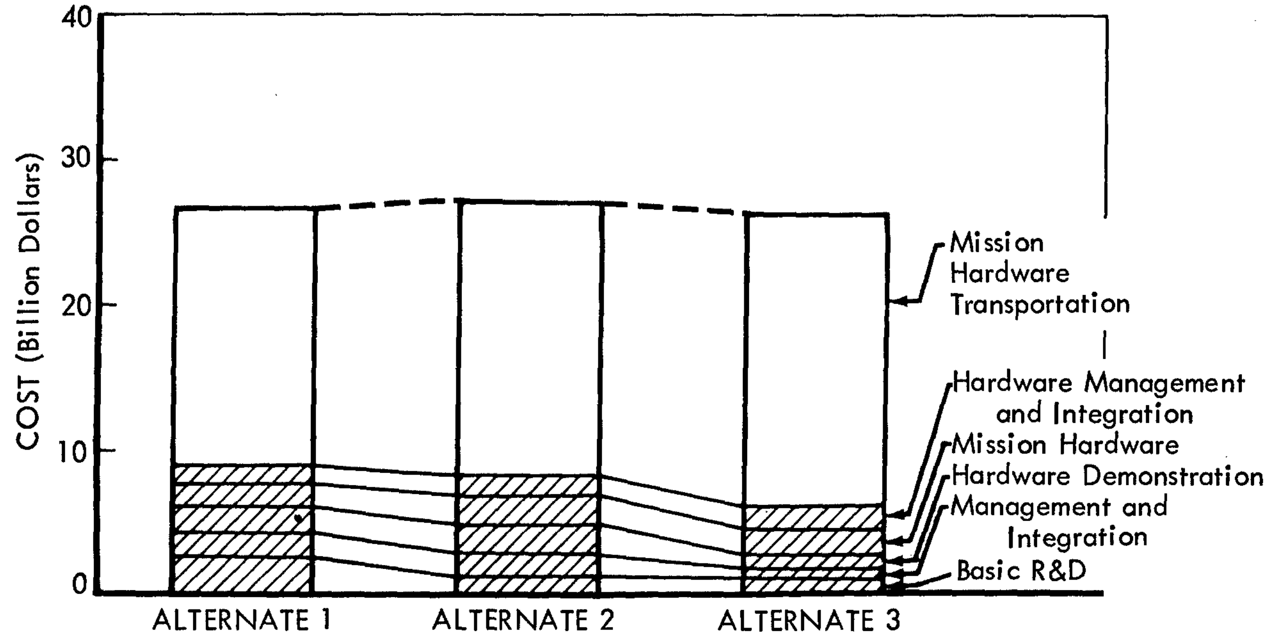
Additional work done on transportation costs for Mars lander missions indicates that marginal transportation costs are less than \$73,000/lb (see Section 4.5).

It appears that there is a decided economic advantage to development of a common SMM for manned space exploration, provided a long-range space program has been defined and sold, and provided adequate definition of all mission requirements is possible at the start of development.

Research Implications

Since the importance of the SMM and the economic advantage of a common design have been demonstrated, structural research should proceed toward satisfaction of multimission requirements.

Deep-space meteoroid environment knowledge must be improved by deploying large-area Pegasus-type probes. An evaluation is required to demonstrate the sensitivity of SMM design to updated meteoroid flux information.



	NONRECURRING							RECURRING				
			FLIGHT TEST									
	R&D	MGMT & INTEG.	HDW.	M&I	TRAN.	Σ	TOTAL	HDW.	M&I	TRAN.	Σ	TOTAL PROGRAM
ALT. 1	2.59	1.65	0.69	0.58	0.60	1.87	6.11	1.55	1.30	17.54	20.39	26.50
ALT. 2	1.18	1.65	0.81	0.69	0.62	2.12	4.95	1.87	1.57	18.57	22.01	26.96
ALT. 3	1.01	0.64	0.34	0.28	0.37	0.99	2.64	1.89	1.59	20.08	23.56	26.20

Cost in Billions of Dollars

Figure 4.2-4: COSTS OF DEVELOPMENT ALTERNATIVES

Multimission requirements should be assessed with a view to what constitutes commonality. Weight is important, and it should be determined what aspects of the structural subsystem can be mission-tailored without violating the fundamental cost advantage of a common module. It is suspected that an external, nonintegrated meteoroid shield could be made mission peculiar.

Study of the common SMM for use as a lunar base should be pursued.

Developmental work in all technologies must proceed with the basic long-life SMM requirements in mind. Maximum advantage should be taken of Apollo and MOL technology. Specific structural research requirements should be further defined.

Time is of the essence. A common design SMM should take over longer Earth-orbit flights after the S-IVB workshop in the early 1970's.

4.3 A "NEW-START" LAUNCH VEHICLE

Launch Vehicle Design Trends

A parametric study was performed to show the effects of cost on configuring a new launch vehicle.

Many configuration decisions would have to be made for a new launch vehicle, given the requirement to develop it. These decisions include choice of propellants, payload size, staging philosophy, and degree of recovery.

The study summarized here considers a two-stage launch vehicle to 100-n mi orbit with payloads of 100,000, 1,000,000, and 10,000,000 pounds. Trade variables are LOX/LH_2 versus LOX/RP-1 first stages and staging velocities from 8000 to 16,000 ft/sec. Second stages are always LOX/LH_2.

The purpose of the study was to compare performance and cost optimized designs.

Cost Elements of Launch Vehicles

Cost trends necessary to evaluate a new-start launch vehicle can be derived from cost data for existing launch vehicle programs.

Launch vehicle stage cost trends were established as part of a program to evaluate program costs for a manned Mars landing mission. These trends are summarized in Figures 2.1-2 and -3, 4.3-1 and -2. Data used for these figures are taken primarily from Reference 2.

Figure 4.3-1 shows the development costs of engines for LOX/LH_2, LOX/RP-1, and storable propellants. The costs shown are for the time from start of program to first-unit production and include ground test units and their testing. They do not include facilities or flight test costs.

Engine development cost correlations show a definite effect of advancing state of the art. The curves shown are for advanced high-pressure engines that were assumed for the manned space exploration studies. Cost-weight equations for the trend lines are indicated.

Engine first-unit recurring costs are shown in Figure 4.3-2. It was found that engine-plus-accessory dry weight gave a better cost correlation than engine thrust, which is often used.

Performance Ground Rules

Assumptions were made on velocity losses, mass fractions, and specific impulse in order to define the family of launch vehicles that would be cost compared.

First-stage thrust/weight was assumed to be 1.25, second stage 1.00. Specific impulse, (I_{sp}), was taken as 446 seconds for LOX/LH_2 (first stage), 355 seconds for LOX/RP-1, and 454 seconds for LOX/LH_2 (second stage). Thrust-to-engine weight was 85 for LOX/LH_2 and 100 for LOX/RP-1. The ratio of stage propellant weight to total stage weight (λ') was taken as 0.92 for LOX/LH_2 and 0.93 for LOX/RP-1.

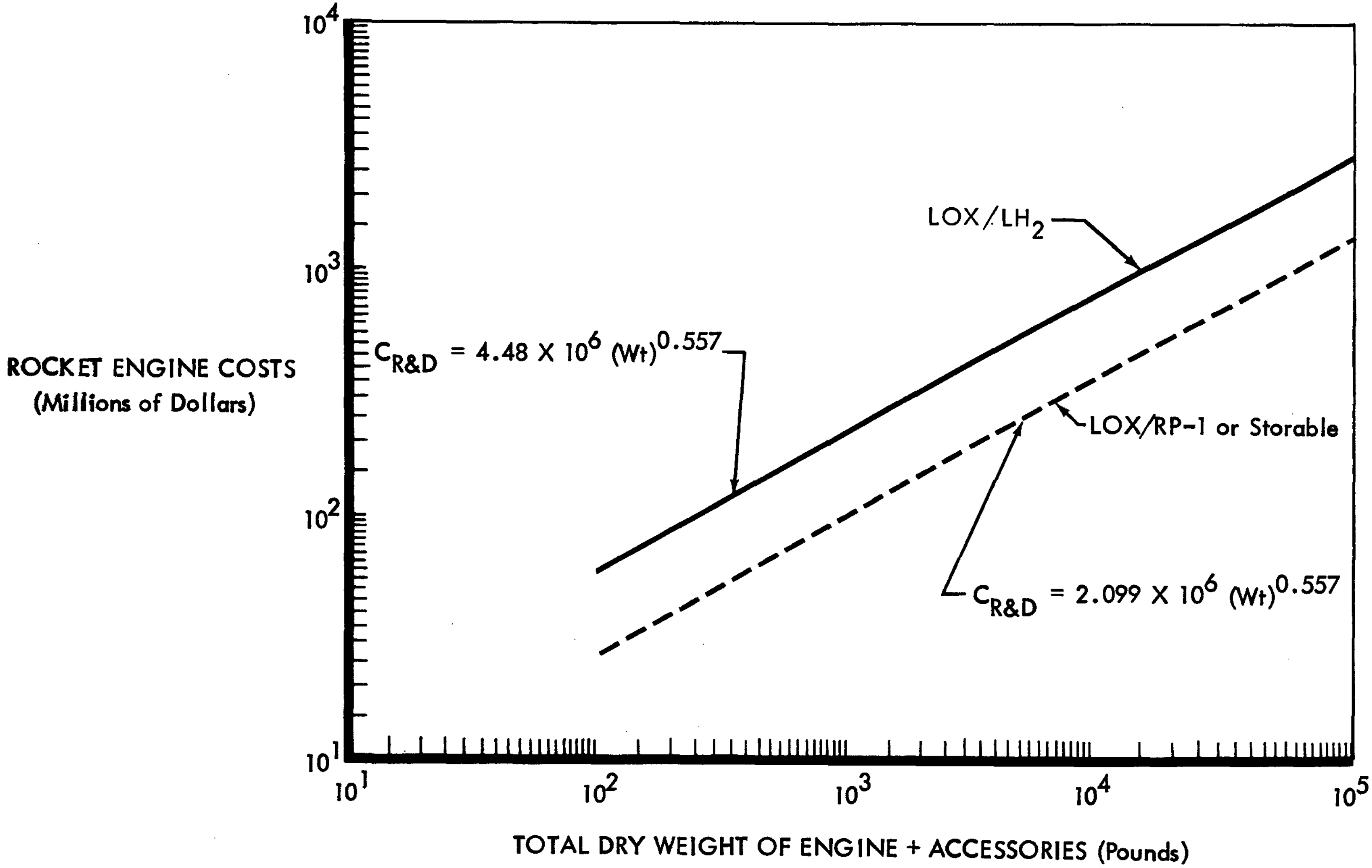


Figure 4.3-1: ROCKET ENGINE DEVELOPMENT COSTS

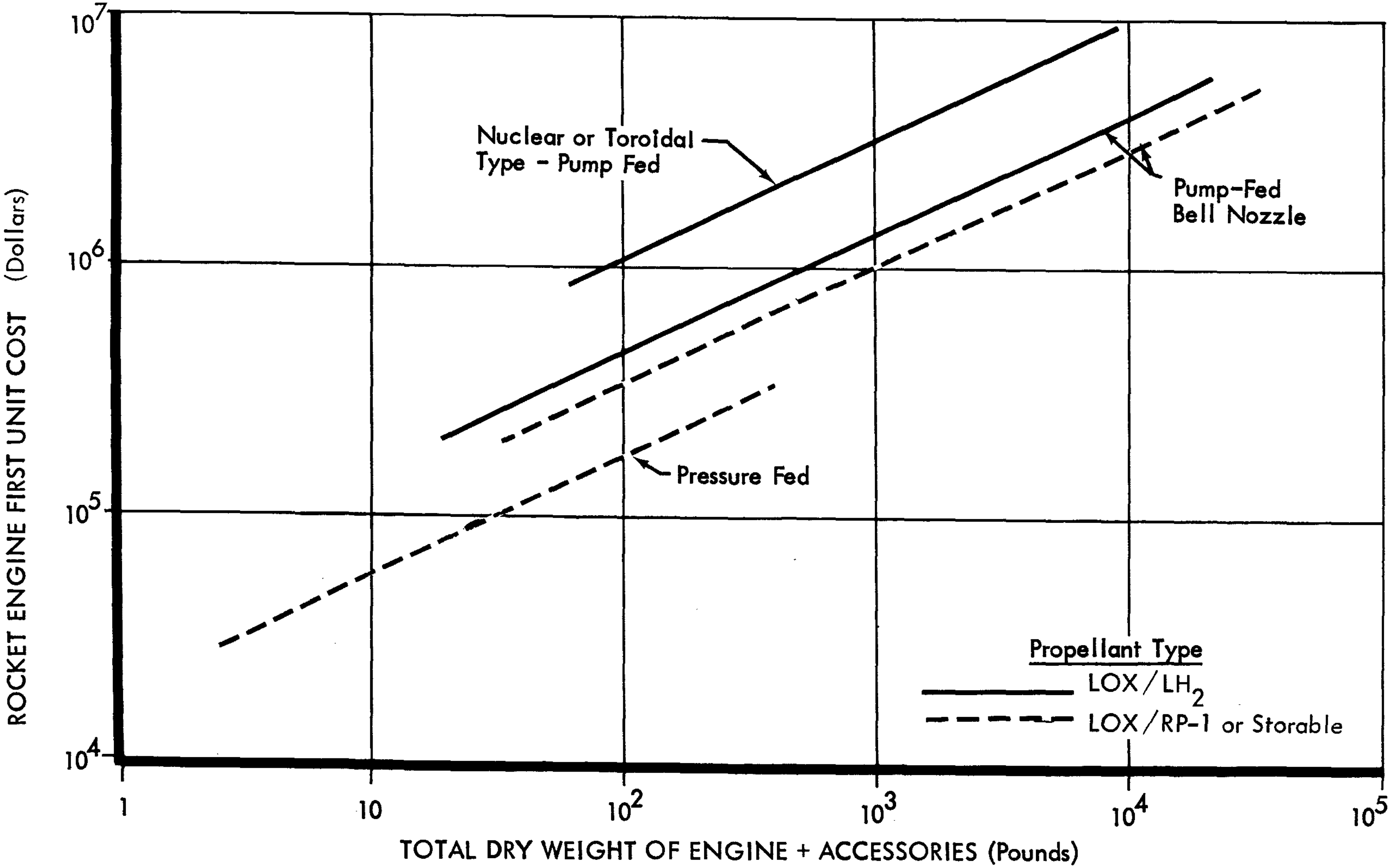


Figure 4.3-2: ROCKET ENGINE RECURRING COSTS

Assumed velocity losses for the LOX/RP-1 stages as a function of staging velocity are shown in Figure 4.3-3.

Launch Vehicle Recurring Costs

Launch vehicles configured by economics have propellants and staging velocities that are different from those found by maximum performance design.

Figure 4.3-4 shows total launch vehicle first-unit cost in millions of dollars versus first-stage burnout velocity, for a payload weight of 1,000,000 pounds. A number of "system type" conclusions can be drawn from this figure (and similar figures for the other payload weights).

1) LOX/RP-1 first stages are more cost effective than LOX/LH_2 first stages for a wide range of payloads, according to current hardware cost data.
2) Staging velocities chosen by cost considerations are higher than those chosen by performance optimization, for a wide range of cost assumptions.
3) A million-pound-payload launch vehicle with a LOX/RP-1 first stage costs 22% more when staging velocity is performance-optimized rather than cost-optimized.
4) Large economic benefits can accrue from economic selection, sizing, and configuration of the next generation of launch vehicles.

One can question why the cost of hydrogen stage inerts really has to be as high as indicated. This appears to be an appropriate question toward which research could be directed.

Figure 4.3-5 is a schematic of the results of this study.

Research Implications

Given the economic requirement for a new launch vehicle, emphasis should be placed on the use of LOX/RP-1 and higher staging velocities, and research associated with hydrogen, for this application, should be minimized.

Launch vehicles using LOX/RP-1 to a greater degree will be heavier than systems that make more use of LH_2, but the bulk density difference may make the vehicles smaller. The first stage of such a launch vehicle would

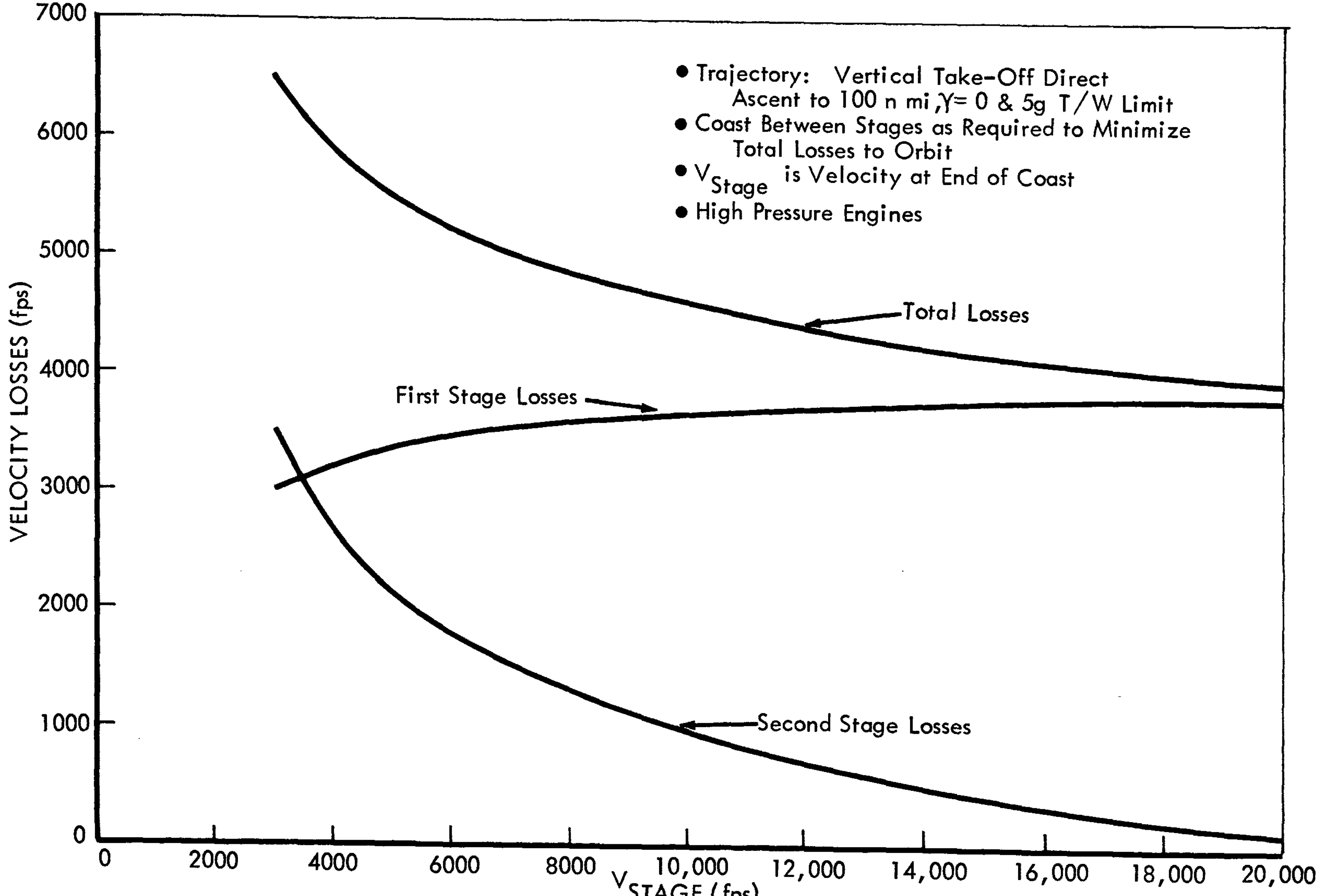


Figure 4.3-3: EFFECT OF STAGING VELOCITY ON VELOCITY LOSSES - LOX/RP-1

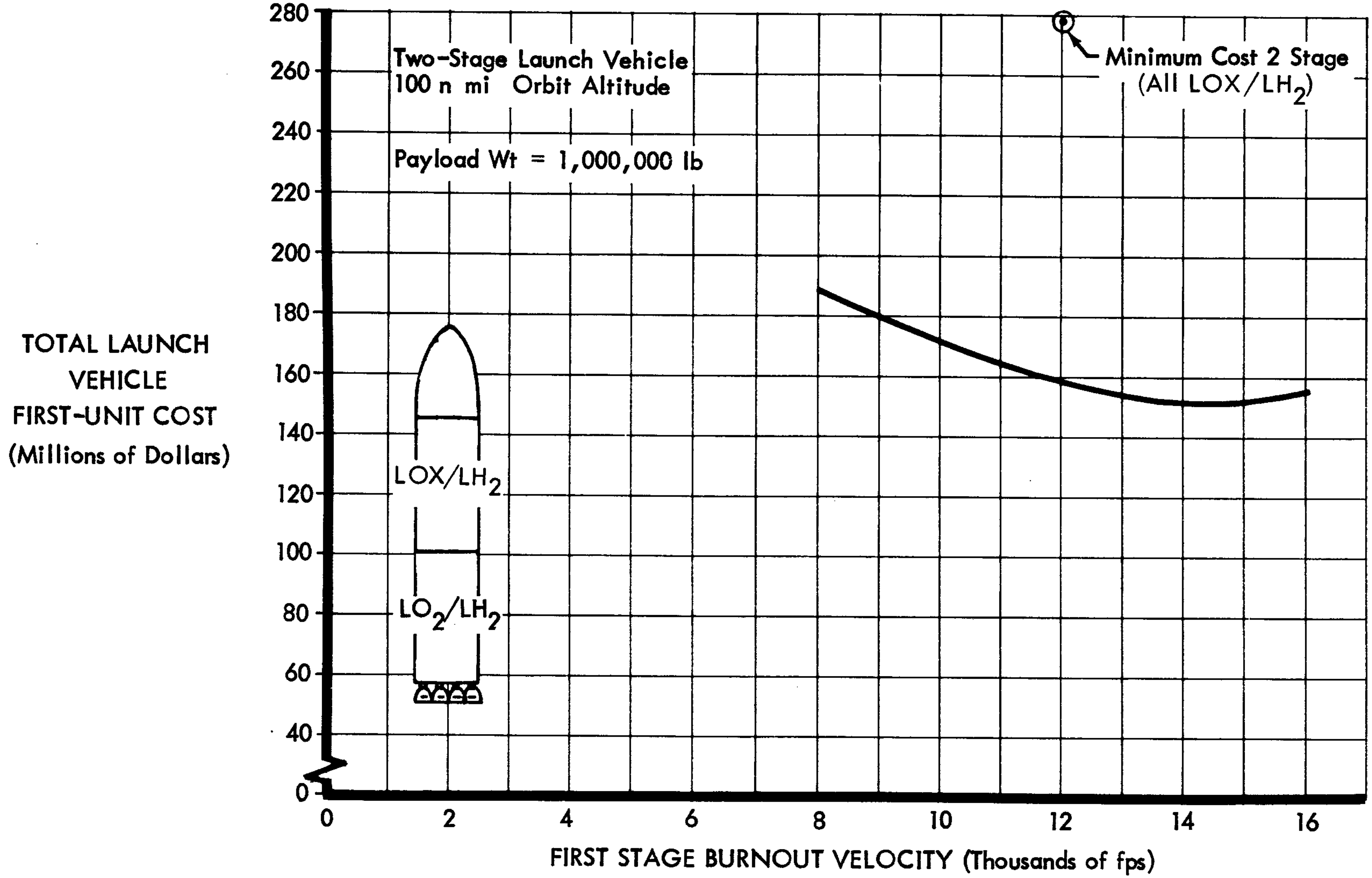


Figure 4.3-4: LOX/RP-1 -LOX/LH_2 LAUNCH VEHICLE STAGING VELOCITY TRADE

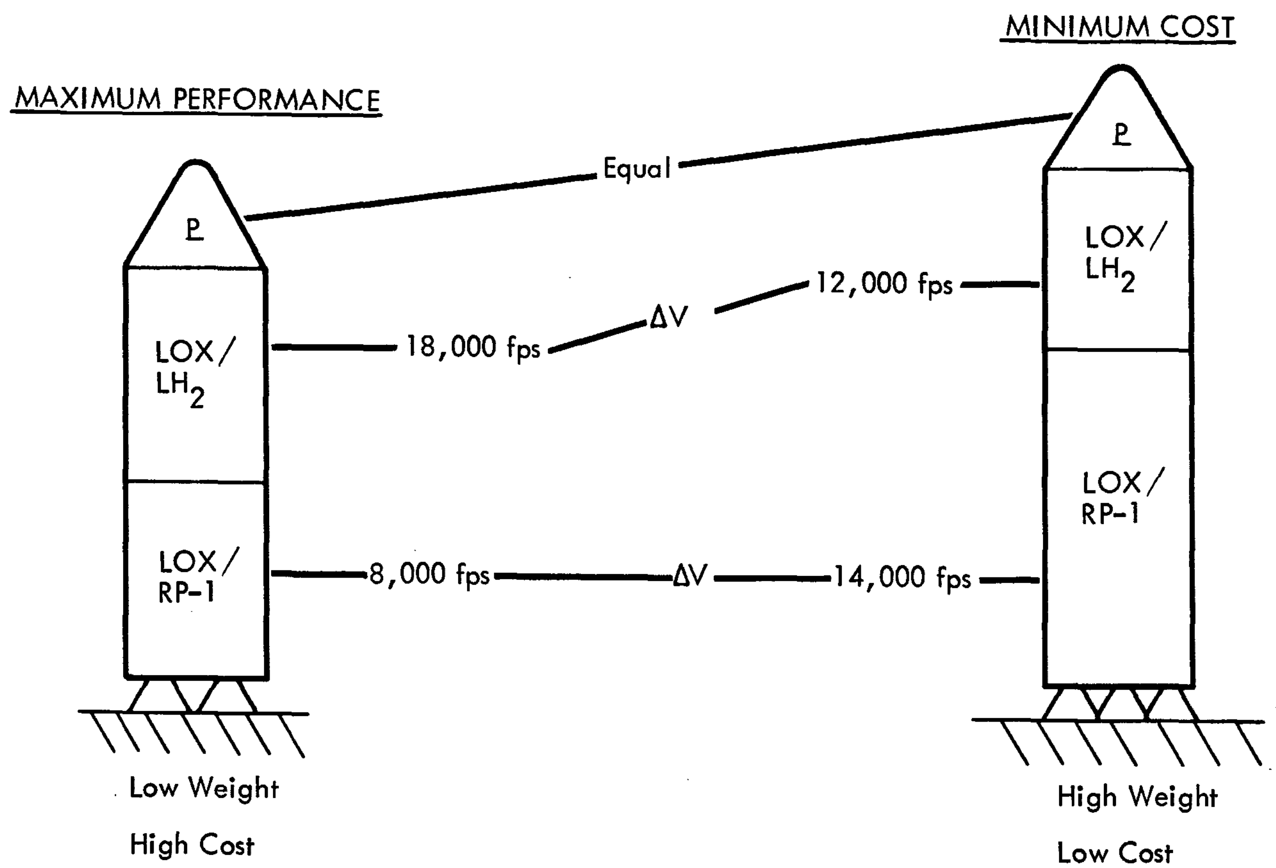


Figure 4.3-5: LAUNCH VEHICLE DESIGN CONTRAST

be very large, and the problems of fabrication and handling probably more severe than on the S-II and S-IC stages. Detailed structural research implications should be studied further.

4.4 EARTH LAUNCH VEHICLE COMPARISON FOR MANNED MARS MISSION

Description of Planetary Hardware and Related Launch Vehicles

Hardware requirements for manned Mars missions dictate the launch of large payload weight aggregates to Earth orbit, which must be achieved economically to minimize program cost.

Previous studies of manned Mars missions show that the mission hardware weight requirements onward from Earth orbit will be on the order of 3,000,000-plus pounds. The elements that make up this weight, and their functions, are shown in Figure 4.4-1. If the two-stage Saturn V with a payload capability near 250,000 pounds were used, 12 launches would be required (assuming maximum use of capability), and orbital assembly, with a 6-per-year launch rate, would require 2 years. These requirements could be cut in half with an Uprated Saturn vehicle, and cut still further with a launch vehicle of the Nova class (1,000,000-pound payload or greater).

The mission configuration, combined with the number of logistics vehicles needed to support assembly- and flight-crew transfers, shows the possibility of six or more interfaces for dividing payload elements. Thus, there are many alternate ways of launching this hardware. Of these, one must produce the least program cost when hardware and operational considerations are fully explored.

Description of Test Program

Following the current trend of manned space programs, a number of demonstration launches is required for mission hardware, increasing the number of launch vehicles, and making their economic selection vital in program planning.

Current trends in testing require the demonstration of mission hardware with four or more flights to man-rate it. Testing requirements must be made even more severe for planetary missions where long duration and lack

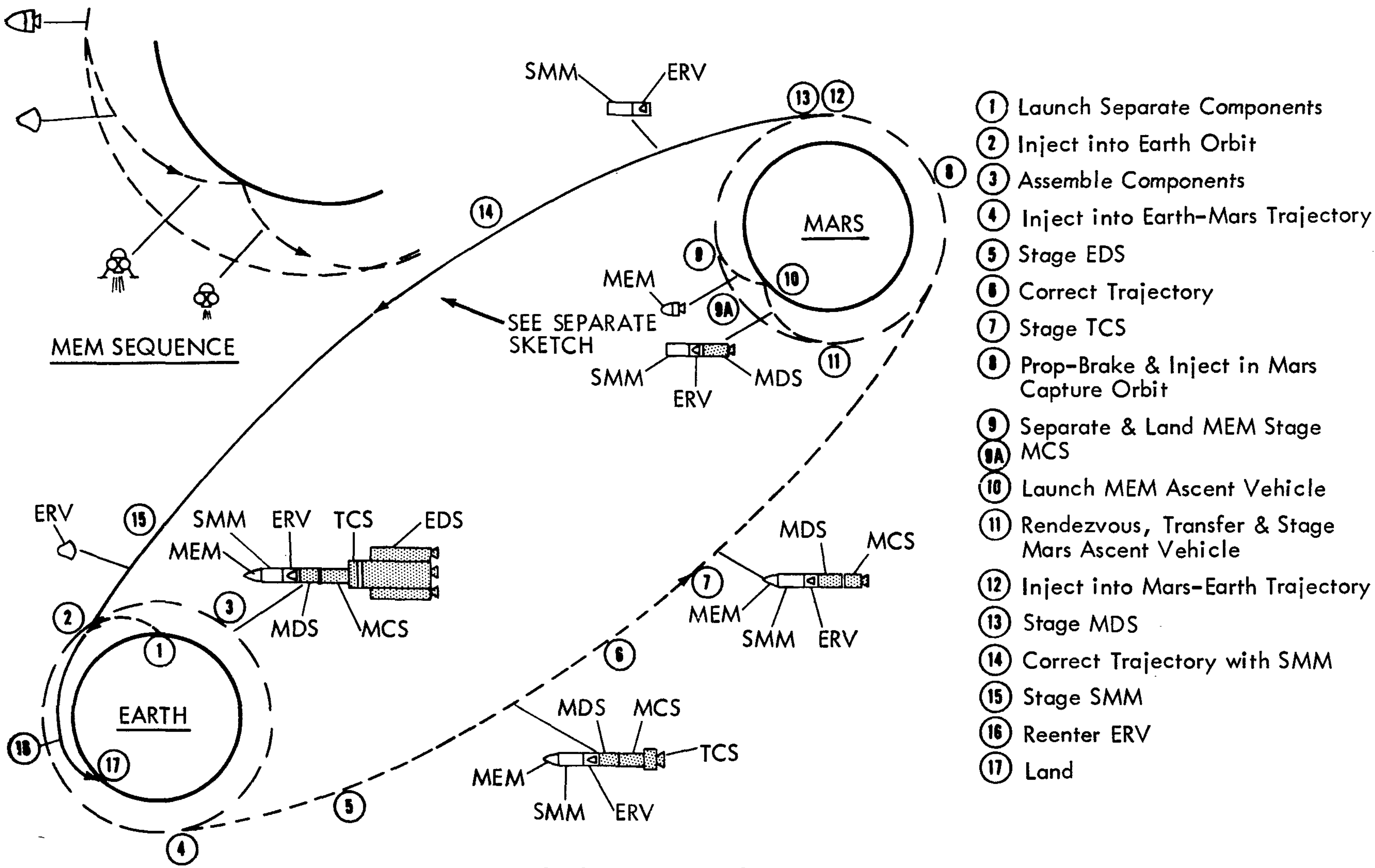


Figure 4.4-1: MISSION DESCRIPTION - MARS LANDER

of abortability multiply the risk of failure. In consequence, the test schedule shown in Figure 4.4-2 is representative of testing requirements for the Mars mission. The advanced nature of nuclear propulsion and planetary aerobraking is reflected in more extensive testing, illustrated by the crosshatched tests. To mitigate the expense of testing, these payloads may be used to perform lesser missions, but launch requirements will be essentially the same in any case.

Testing plus operational flights lead to launch vehicles contributing between 40 and 50% of the cost of landing men on Mars. Thus, the economic choice of launch vehicles is a powerful approach to program cost savings.

A corollary is evident in the need for cost effective test planning in which cost and mission risk are balanced.

Choice of Launch Vehicles

Launch vehicles for manned Mars missions can be selected from the proposed Uprated Saturn family, or a new-start launch vehicle can be configured to match specific program requirements.

Hardware elements for manned Mars missions range in weight from the Earth return vehicle (ERV) at 20,000 to 30,000 pounds to the Earth depart stage (EDS) that may vary in weight up to 2,000,000 pounds (depending on propulsion concept) and may or may not be modularized. Consequently, launch vehicles can be chosen from existing boosters, upratings of these boosters, or new booster configurations. Major candidates are shown in Figure 4.4-3.

Simplifying the Alternatives

A preliminary screening can reduce the very large number of launch vehicle alternatives available to launch mission hardware elements.

Many possible combinations of launch vehicle and payload can be made from the elements available. Not all will be cost effective, however, and preliminary eliminations can be made. For example, it will not be cost effective to develop two Uprated Saturn vehicles to match two different

TEST	TESTS PERFORMED			
1	MEM Tests	Module Test		
2		First EDS Test	First MCS Test	First ERV Test (Also First MDS Test)
3		Second EDS Test	Second MCS Test	Second ERV Test (Also Second MDS Test)
4			Third MCS Test	
5	First Unmanned Total Vehicle			
6	Second Unmanned Total Vehicle			
7	Manned ERV + SMM Test			
8	First Manned Total Vehicle			
9	Second Manned Total Vehicle			

Figure 4.4-2: PROGRAM TEST REQUIREMENTS

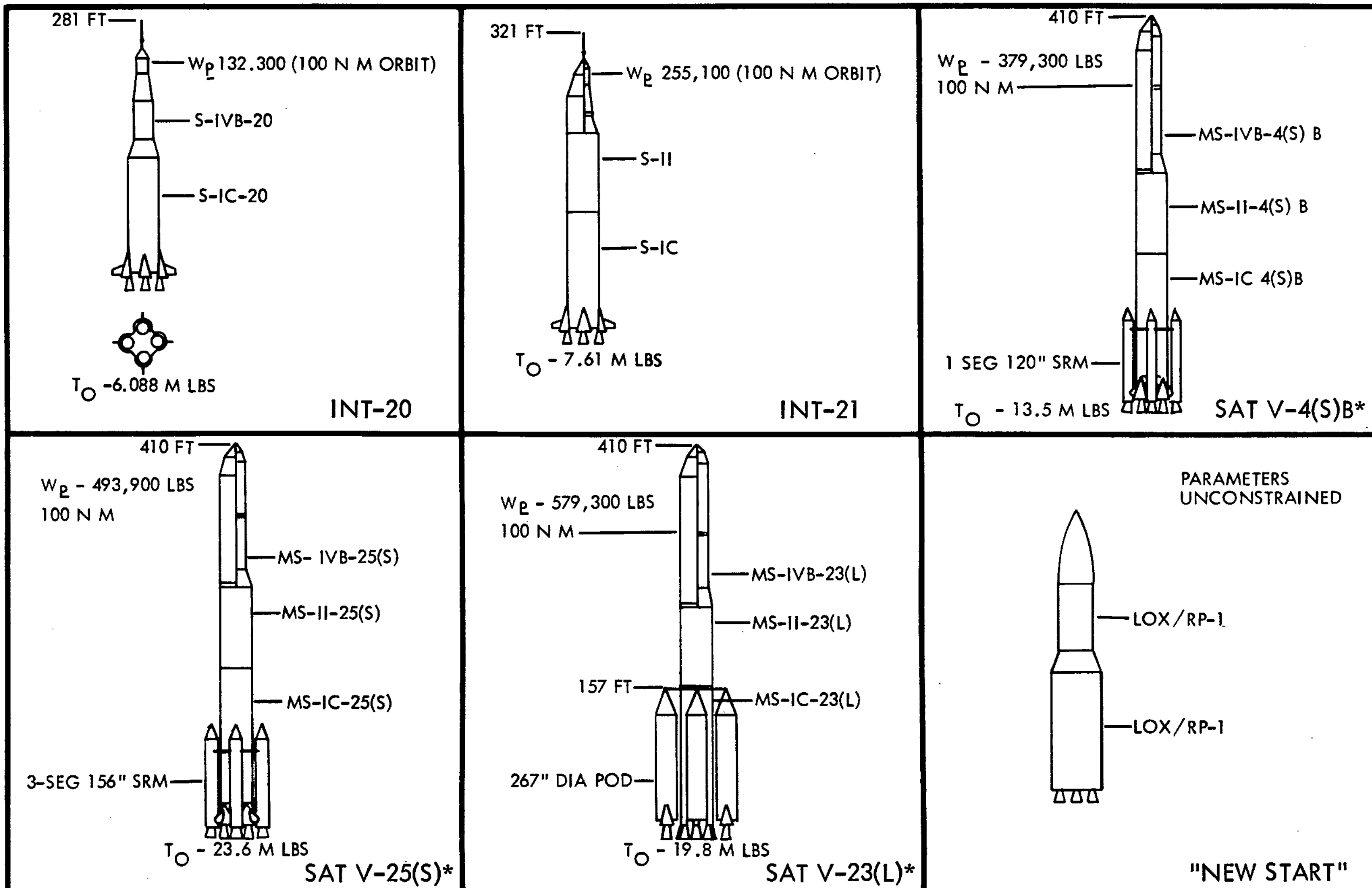


Figure 4.4-3: UPRATED SATURN AND "NEW START" LAUNCH VEHICLE

*Two Stage Versions Used For This Study

payload levels if the development cost of the smaller, when prorated against the number of program flights required, exceeds the difference in recurring costs of the two vehicles. Similarly, the high development cost of a new-start launch vehicle will preclude the companion use of a large Uprated Saturn.

The extension of such arguments, presented fully in the backup document, reduces the number of choices to five major alternatives:

1) Choice of a launch vehicle set selected from the Uprated Saturn family;
2) A new vehicle that launches the total mission array in three shots;
3) A new vehicle that launches the total mission array in two shots;
4) A new vehicle sized to launch the EDS;
5) A new vehicle that launches the total mission array in one shot.

Results of Selection

Study results for modularized mission-propulsion elements show that several launch vehicle options can be cost effective, depending on mission requirements.

Mission propulsion elements that are subdivided into smaller modules present the greatest opportunity for launch vehicle trades. Economic comparisons of launch vehicles, made on such a configuration for nuclear propulsion, are shown in Figure 4.4-4. Launch vehicle costs for the five major options are shown for various levels of Mars excursion module (MEM) weight. No single option dominates the choices, and new launch vehicles can be justified economically at almost all MEM weight levels. These have, for mission vehicles that vary in weight from 2.45 to 3.61 million pounds, payload capabilities ranging from 1.07 to 2.07 million pounds.

A machine program developed to perform this launch vehicle selection for any combination of mission hardware weights is described further in the backup document.

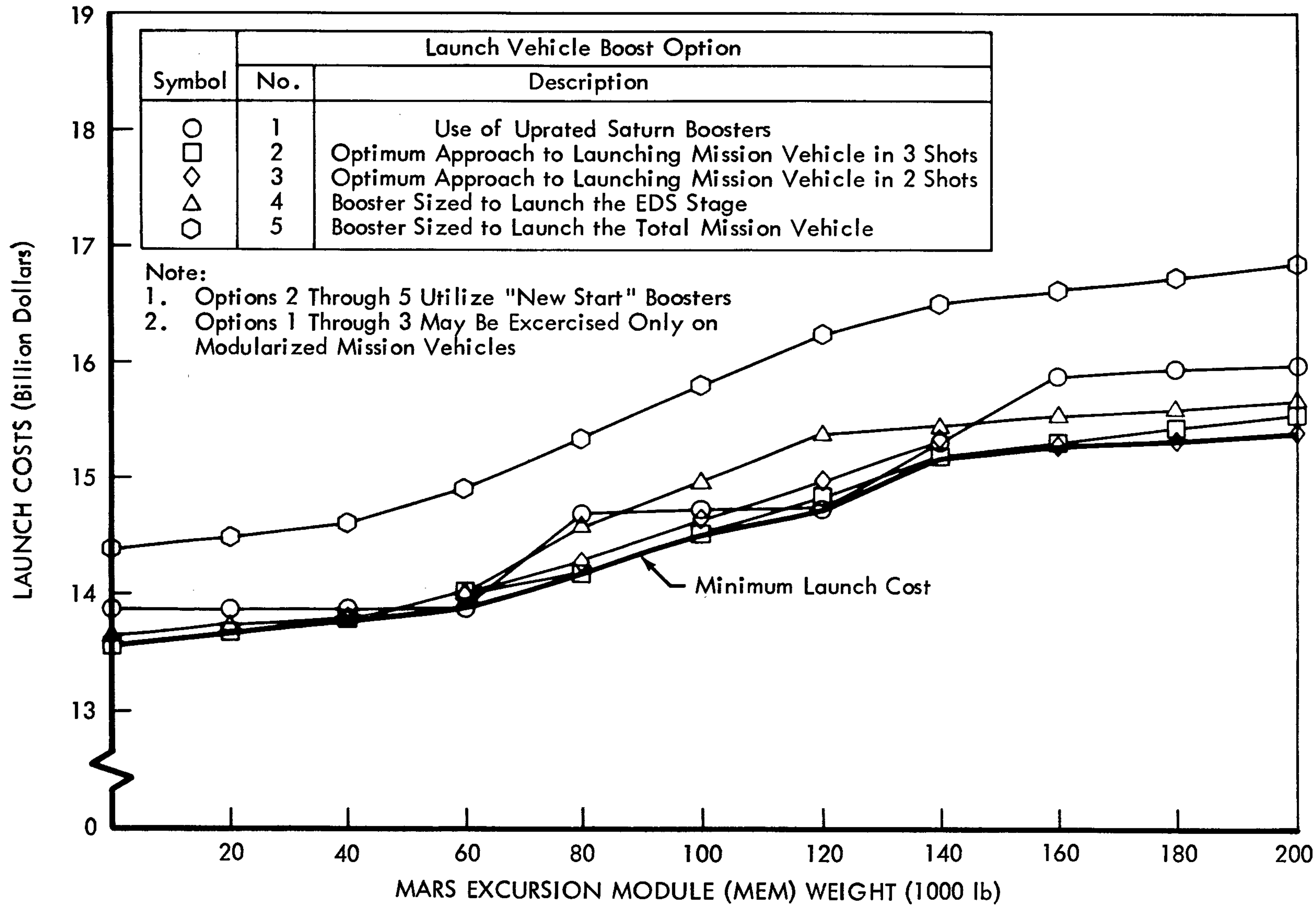


Figure 4.4-4: RESULTS OF LAUNCH VEHICLE SELECTION

Research Implications

Economic selection of launch vehicles for a manned Mars mission shows need for continuing structural research on uprating the Saturn V launch vehicle and on developing new-start launch vehicles of the Nova class.

The launch vehicle cost program considers all of the major elements associated with launching arrays of space hardware over long periods of time. The cost results (Figure 4.4-4 is typical) are thus valid for comparisons of Uprated Saturn and Nova-class launch vehicles.

Further study of Nova-class vehicles is required to verify the performance and cost ground rules used in obtaining these results. It may be that, by stressing economy in design, even lower costs for new vehicles can be obtained.

Further study and development of Uprated Saturn is also indicated to determine: (1) the optimum approach to uprating (increased first-stage size and burnout velocity is indicated in Section 4.3), and (2) if potential cost savings can be realized with these boosters.

4.5 COST SENSITIVITIES FOR A MANNED MARS MISSION

Identifying High-Leverage Research Items in an Advanced Space Mission

Structural research for a future manned planetary mission should be directed at hardware areas that most strongly affect total program costs.

Some program benefits will accrue from any technological advance that can be made for future space hardware. Not all such advances will be equally valuable, however, and with limited resources, not all technological areas can be pursued. Some means are required to identify technological areas that will produce maximum gains.

The space program is no longer limited by technical feasibility; it is now limited by cost. The scope of future space missions, and probably their very occurrence, depends on the ability to do them cheaply. Therefore, the criterion for defining research gains must be cost.

This reasoning implies the necessity for a study to evaluate the sensitivity of total space program cost to various potential hardware improvements that may arise through technical research. Figure 4.5-1 depicts the leverage available in research performed now to effect program cost savings at a future date.

Description of Mission

A manned Mars mission was selected for detailed study because it represents the most difficult mission currently contemplated, because it contains essentially all the advanced technology features required in the next 20 years, and because it is far enough advanced in time that early cost planning can produce significant benefits.

Landing a man on Mars would be a major goal in space. Such a mission requires the ability to place payloads of more than 600,000 pounds in Mars orbit and to return nearly 100,000 pounds to Earth from Mars. It also imposes life requirements in excess of 1 year on the hardware. As such, it will place the greatest burden on launch vehicle capability and technology of any currently considered program.

Because the Mars lander mission requirements will dictate many new hardware developments, the opportunity exists to apply cost decisions during the earliest phases of the program. Figure 4.5-2, a development schedule for the mission, shows the necessity for timely application of cost. The long lead times associated with developing Mars mission hardware require immediate consideration of cost in planning this mission.

Alternate Concepts

By studying propulsion concepts, planetary aerobraking, and modularity of propulsion elements, the significant program decisions for the mission are considered.

There are many technical aspects to the Mars lander mission. Application of the technique discussed in Section 2.3 resulted in identification of

Figure 4.5-1: HIGH LEVERAGE ITEMS

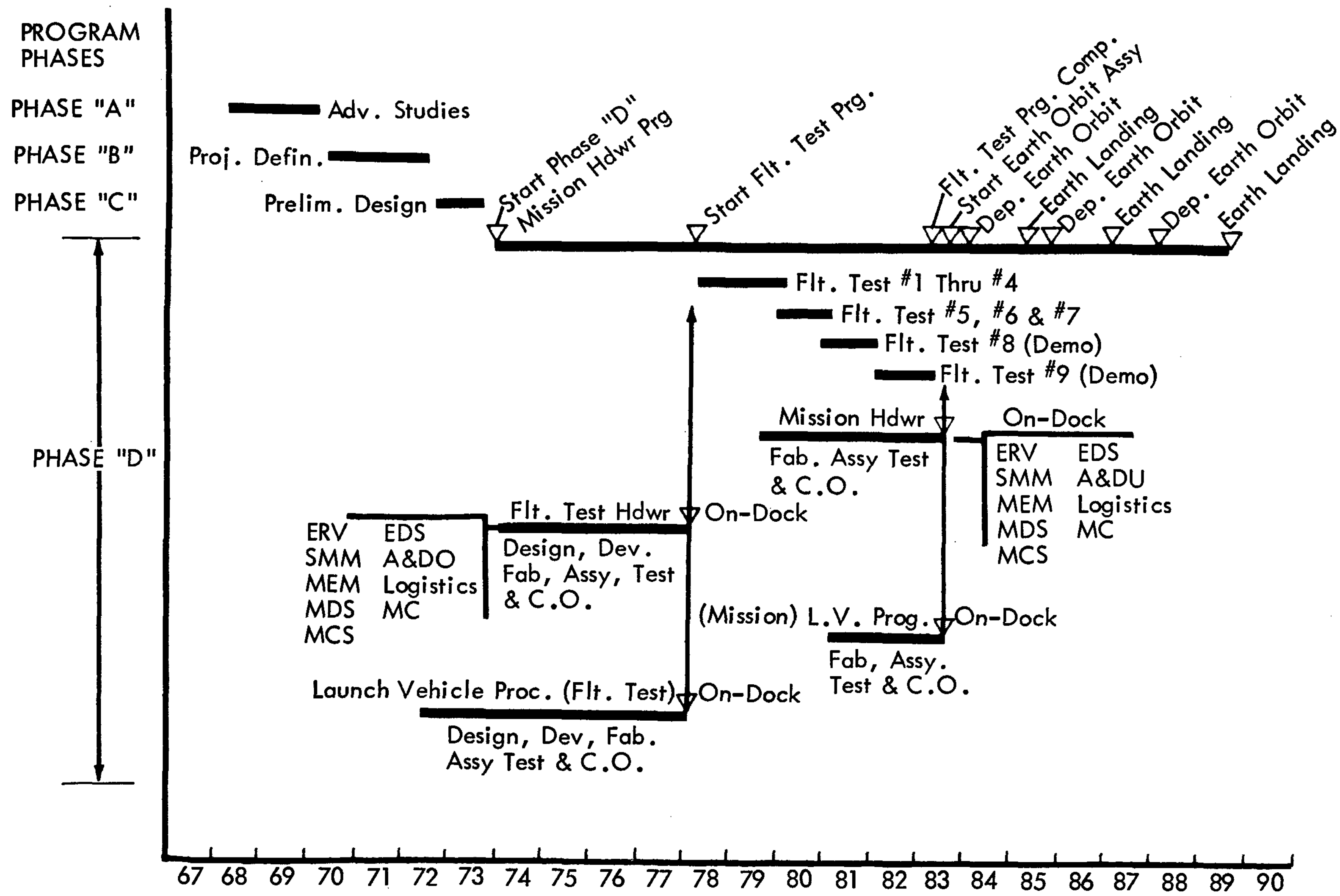


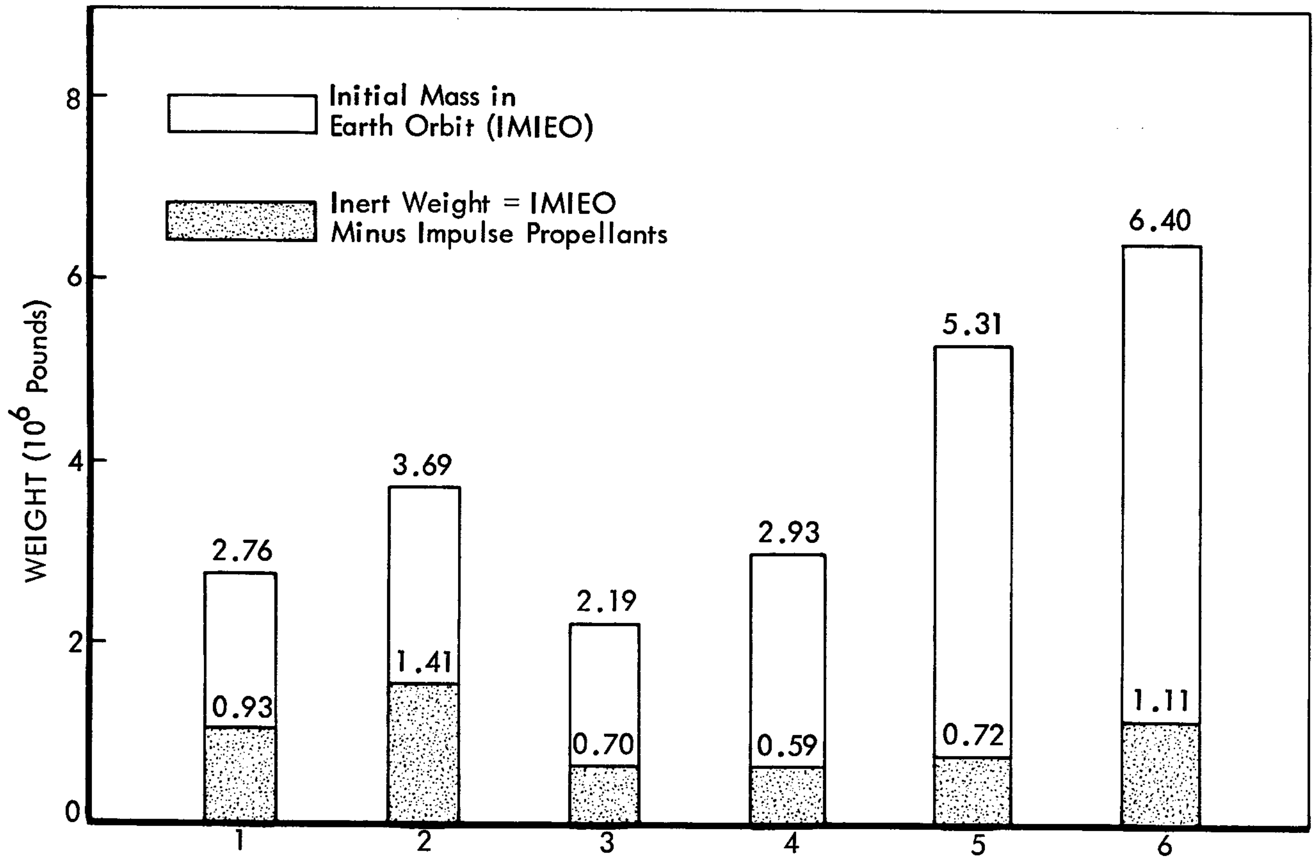
Figure 4.5-2: MARS LANDER PROGRAM SCHEDULE

six principal alternatives for performing this mission. These are characterized by: (1) the choice of LOX/LH_2 or nuclear propulsion to perform major velocity changes in space; (2) the use of propulsion or aerodynamic braking to capture the planet; and (3) the design of a single propulsion module (which can be clustered) or separate, optimized propulsion stages to perform Earth-orbit departure, planetary capture (if propulsive), and planetary orbit departure. Economic screening identified the most promising combinations of these choices.

Figure 4.5-3 identifies these concepts and shows their associated values of initial mass in Earth orbit (IMIEO). Detailed costing exercises for each of these concepts, using a set of baseline mission ground rules, shows the following program cost comparison:

Concept	IMIEO (million lb)	Program Cost ($ billion)
1	2.76	30.71
2	3.69	27.87
3	2.19	26.58
4	2.93	26.17
5	5.31	33.18
6	6.40	29.87

Of these, Concept 2 (the modularized-stage all-nuclear design), and Concept 4 (the LOX/LH_2 design with aerobraking) show most promise in their separate areas. All data to follow will be based on Concept 2 because it represents a recommended concept (Reference 11), except for sensitivity studies specifically associated with aerobraking, where Concept 4 is used. Sensitivity data for the other concepts is tabulated in the backup document, D2-114116-2.



	1	2	3	4	5	6
Earth Depart	Nuclear	Nuclear	Nuclear	O_2/H_2	O_2/H_2	O_2/H_2
Mars Capture	Nuclear	Nuclear	Aero.	Aero.	O_2/H_2	O_2/H_2
Mars Depart	Nuclear	Nuclear	O_2/H_2	O_2/H_2	O_2/H_2	O_2/H_2
Remarks	Optimum	Modular			Optimum	Modular

Figure 4.5-3: MANNED MARS LANDER CONCEPTS
Weight Comparison

Program Costing Philosophy

Program cost elements were subdivided only to the smallest level necessary to detect significant effects.

The difficulty of costing a space program becomes increasingly severe as smaller program cost elements are used. Thus, no finer subdivision of cost should be employed than is necessary to show the important cost relationships.

Figure 4.5-4 shows the program cost element matrix used during this study. Hardware elements are subdivided to the module level. Each item represents a staged component of the mission array. Their costs were actually further subdivided because cost trends for these elements were drawn from earlier, more detailed studies, such as those described in Sections 4.2 and 4.3.

The horizontal elements were individually estimated and represent the minimum necessary subdivision. Note that what is more commonly called R&D, the nonrecurring cost, actually consists of seven items of major importance.

Study Approach

Program costs were estimated in detail for a baseline design and were then programmed to permit machine calculation of sensitivities.

Figure 4.5-5 shows the study approach used to determine sensitivities. Baseline costing exercises, conducted manually, were used to identify costing methods required, to develop a machine program for weight predictions, and to show the necessary steps in programming cost predictions.

The study procedure consists of identifying the sensitivity area to be considered, revising the baseline data to reflect the desired parametric variation, recomputing mission element weights that result from these variations, applying these weights to the mission hardware cost prediction

Hardware Element	COST ELEMENT												
	NON-RECURRING COSTS							RECURRING COSTS					
	Basic R&D	Demon-stration Hardware	Launch Site	Launch Ops.	Flight Ops.	Recovery	Inte-gration & Mgmt	Mission Hardware	Launch Site	Launch Ops.	Recovery	Inte-gration	Total Program
ERV													
SMM													
MDS													
MEM													
MCS													
MIDCOURSE													
A&D.U.													
LOGISTICS													
FLIGHT OPS.													
RECOVERY													
L/V													

Figure 4.5-4: PROGRAM COST ELEMENT MATRIX

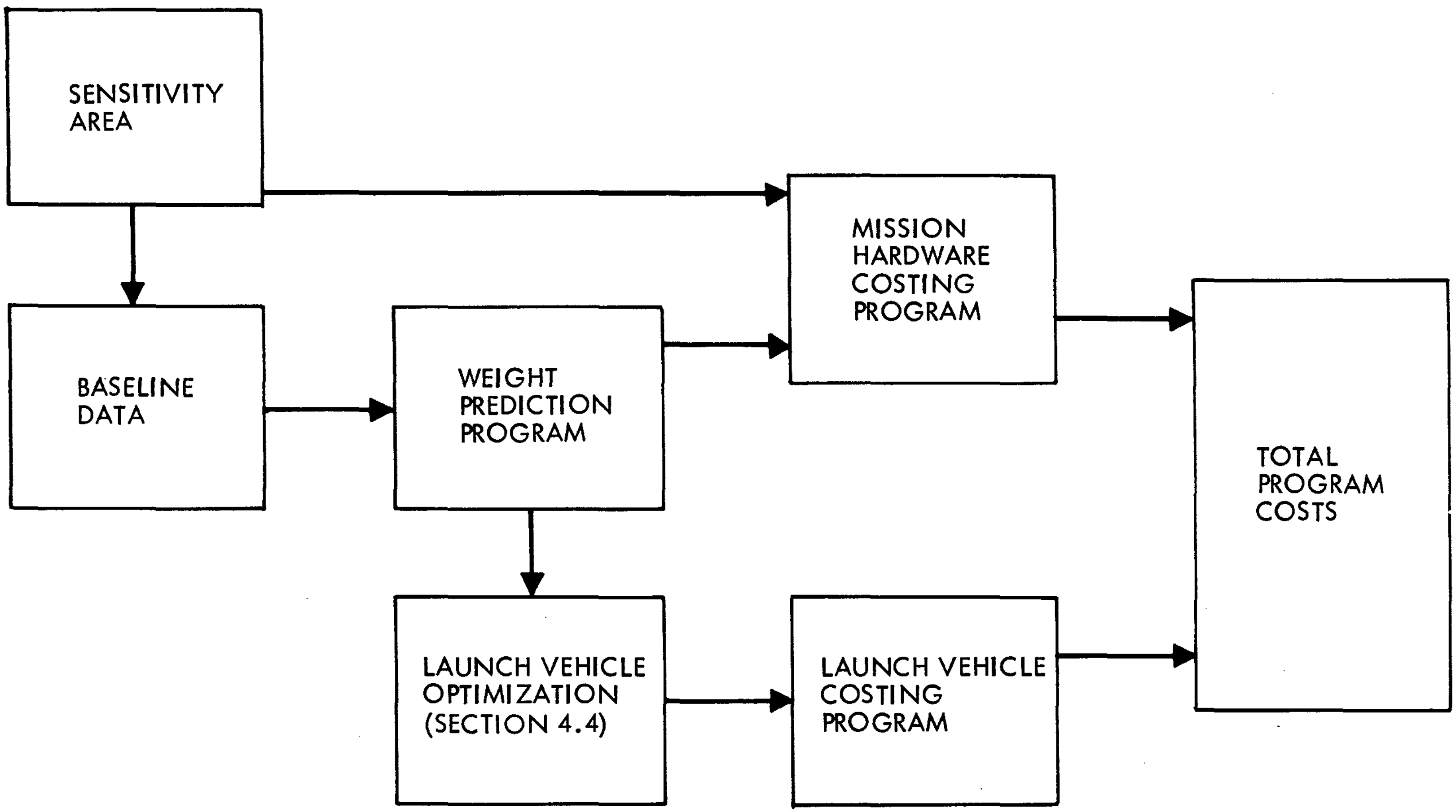


Figure 4.5-5: STUDY APPROACH

program to estimate their contribution, applying the same weights to the launch vehicle optimization routine (described in the previous section), using the selected launch vehicles in the launch vehicle costing program to predict their costs, and finding total program costs that result from the sensitivity area considered.

An alternate path is used in one specific study where the sensitivity considered is that of total cost to certain mission hardware costs, so that these sensitivities are applied directly to the cost program.

Sensitivity Areas Assessed

Cost sensitivities were obtained for significant structural aspects of propulsion elements, SMM, MEM, and ERV, and include meteoroid shielding, thermal protection, and primary and secondary structure.

Cost sensitivities were aimed at detecting the program cost implications of structural design areas. These sensitivities were approached from the standpoint of weight variations, but the weight variations considered may, by interpretation, be related to reliability or other aspects of design. All mission hardware elements were studied, but most attention was given to primary propulsion elements and to the hardware returned to Earth: the ERV and SMM.

The ERV and SMM were considered together because they effectively form a single element for the duration of the mission up to a few hours before Earth entry. Although it was intended to study structural weight variations, the sensitivity results for these elements are valid for any other aspect of their weights, and thus apply to other subsystems and to fluids, experiments, and nonjettisoned expendables.

Propulsion modules have three major structural weight items apart from propulsion systems: primary structure, meteoroid shielding, and cryogenic insulation. All three were examined.

Total weight variations of the MEM were studied. As in the case of the ERV-SMM package, these variations may be ascribed to any of the MEM weight elements.

The one study that did not use Mission Concept 2 was an examination of the sensitivity of the thermal protection system weight required for planetary aerobraking. Concept 4 was used. A special trade was conducted to show the relative worth of cost and weight reductions in the propulsion stages.

Sensitivity Results

Study results show marginal costs of weight reductions up to \$160,000/lb and demonstrate major cost motivations for structural research.

Sensitivity results are presented in plots of total program cost or cost change against absolute weight, weight change, or percentage weight change from a baseline, as appropriate.

Figure 4.5-6 shows sensitivities of \$160,000/lb for variations in the weight returned to Earth. This number can be interpreted as the marginal transportation cost for the Mars mission if one operational flight is made.

Figure 4.5-7 shows total program cost variations for changes in MEM weight. Three possible designs are shown, all of which use initial ballistic descent, with different concepts for final velocity reduction and landing. The baseline, with storable propellant, has a program cost of \$27.87 billion. Use of mild cryogenics ($FLOX/CH_4$) in the MEM reduces this by \$1.1 billion, and an all-aerodynamic descent stage using parachutes produces a total cost reduction of \$1.55 billion.

Figure 4.5-8 presents sensitivities of the various structural aspects of propulsion modules. Note the importance of meteoroid shielding, at 5 lb/ft^2 for the baseline, in cost reductions. It appears that weight reductions in tank structure, at 2 lb/ft^2 for the baseline, will also be effective if they can be made for somewhat lower costs. Cryogenic insulation does not represent a sufficiently important weight item to merit attention to weight reductions. However, its technical feasibility must be assured.

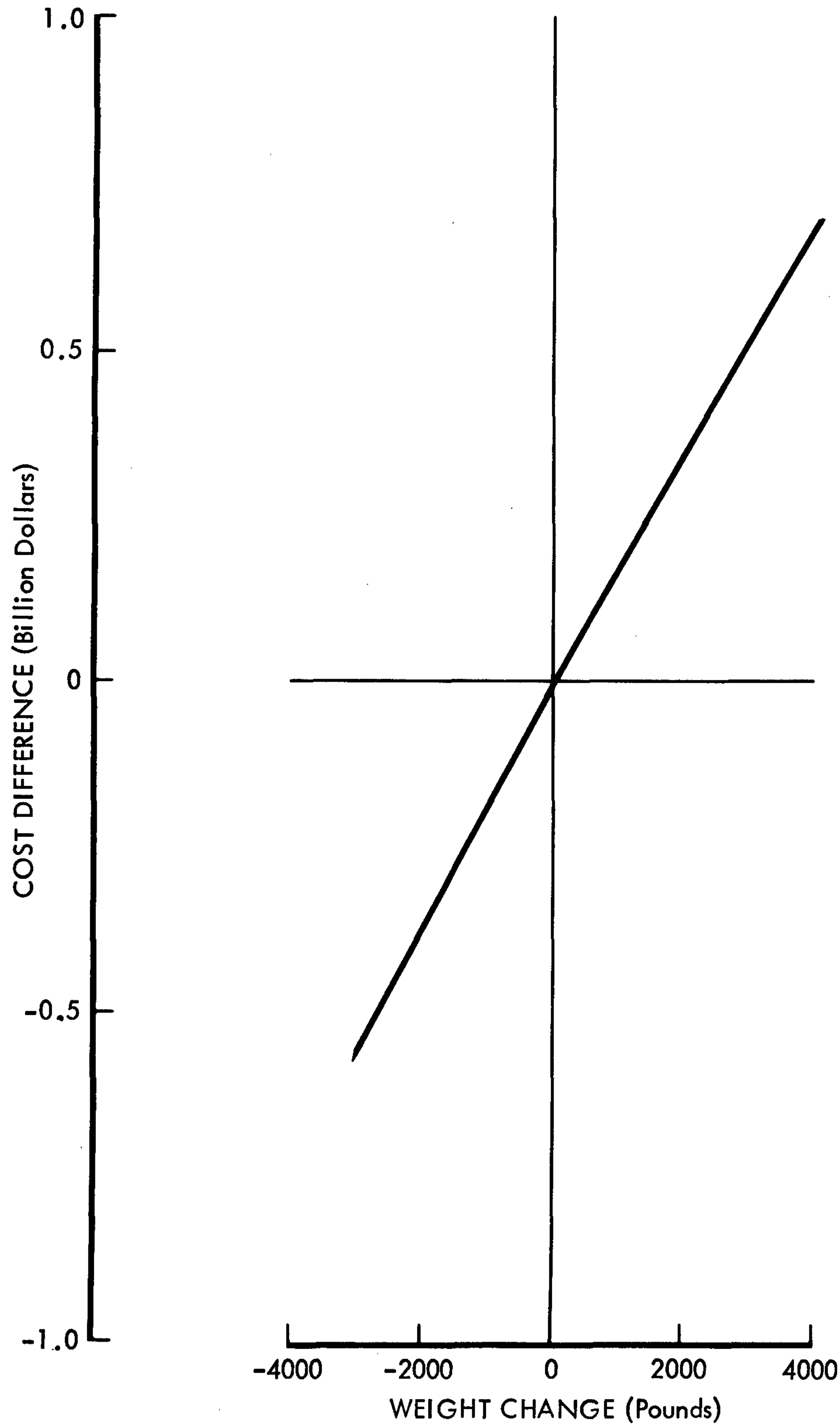


Figure 4.5-6: PROGRAM COST SENSITIVITY TO EARTH RETURN WEIGHT

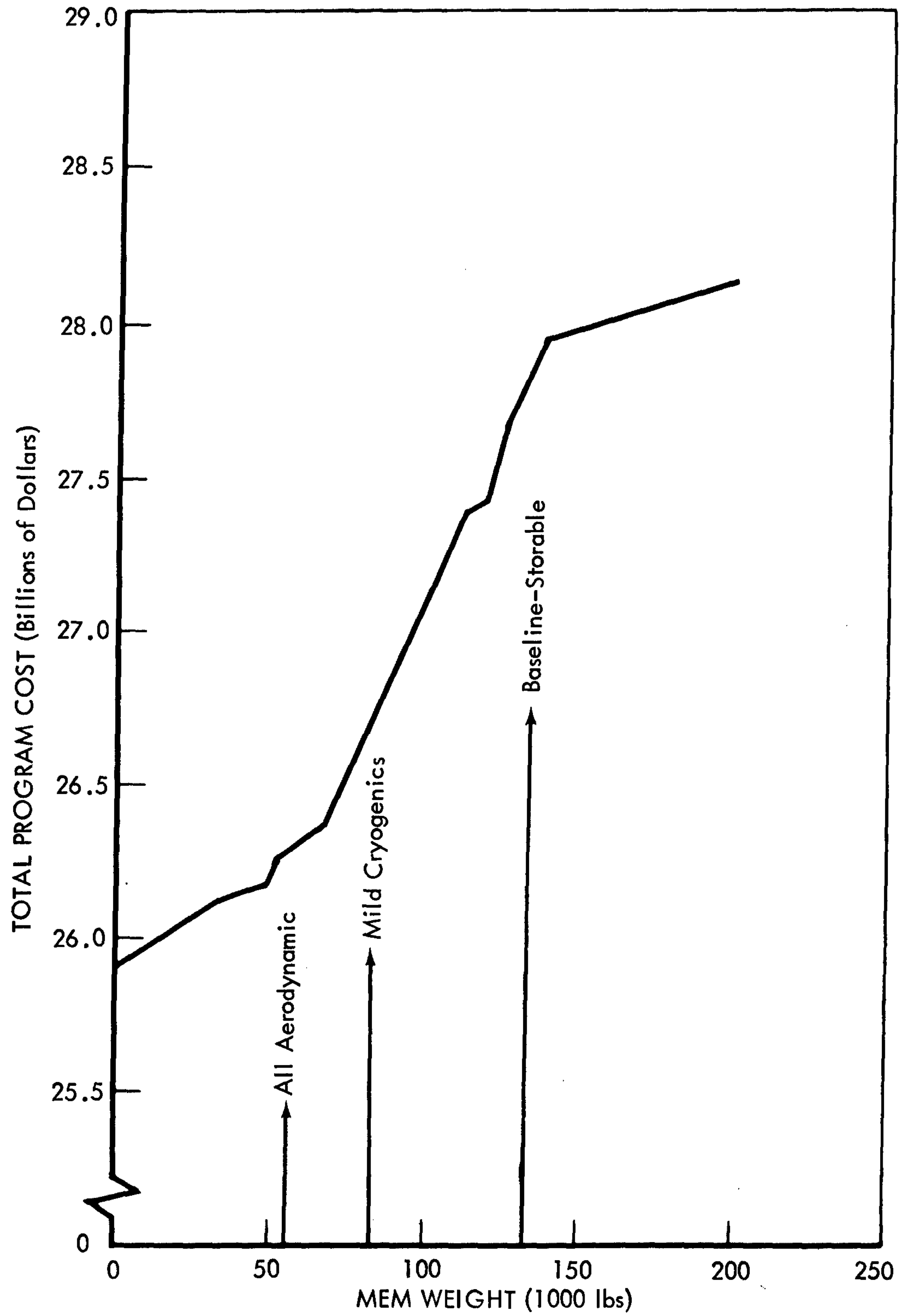


Figure 4.5-7: PROGRAM COST SENSITIVITY TO MARS EXCURSION MODULE WEIGHT

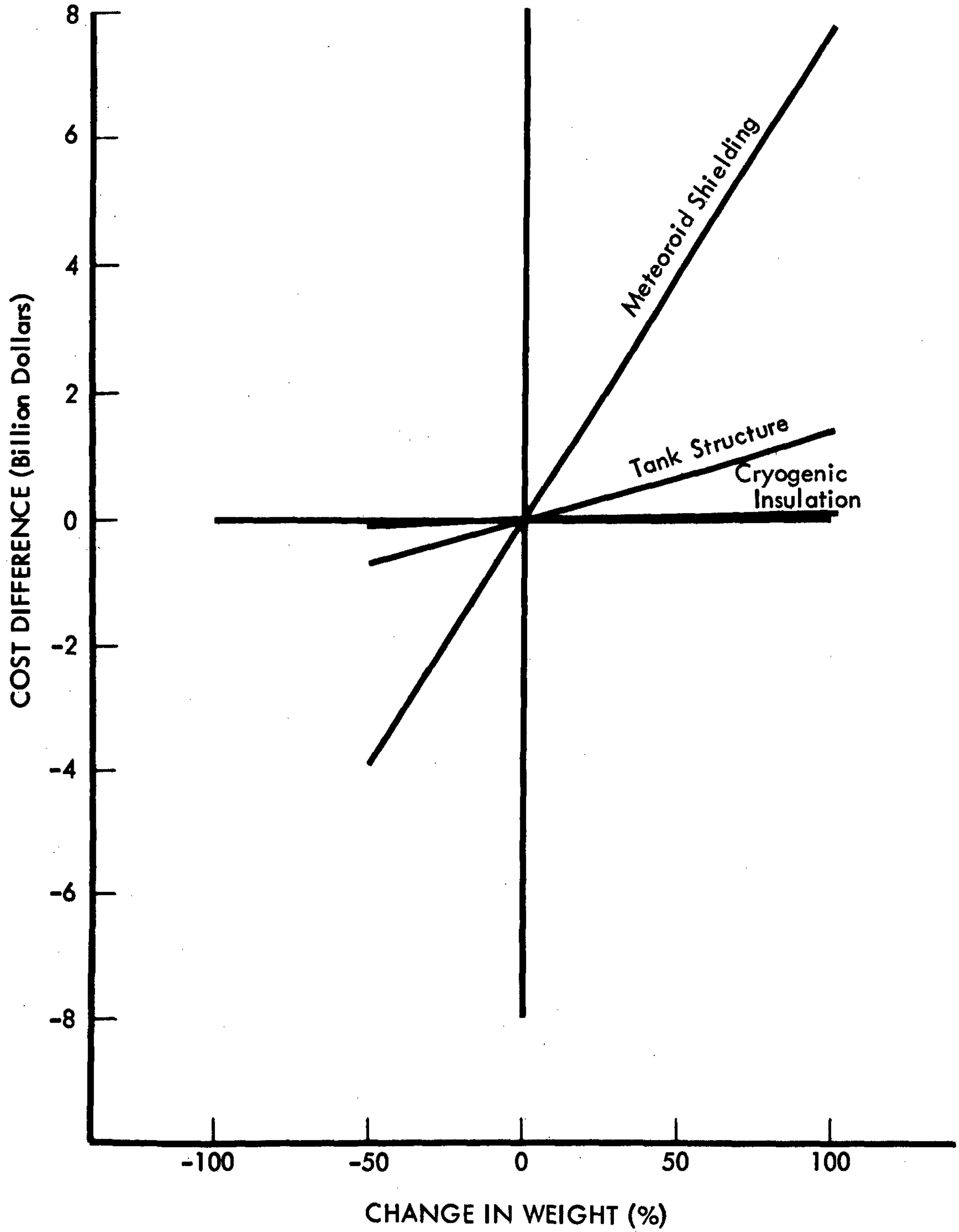


Figure 4.5-8: PROGRAM COST SENSITIVITIES TO PROPULSION MODULE STRUCTURAL WEIGHTS

Figure 4.5-9 shows the value of reducing planetary aerobraking ablation material weight. At 2 to 3 lb/ft^2 on the average, improved material technology could easily produce a 25% weight reduction; 50% reductions are possible with further research.

Figure 4.5-10 presents the cost significance of errors in predicting the meteoroid flux for Mars missions. Exposed areas and exposure times are such that large cost sensitivities are involved. A change in wall configuration, eliminating some weight items, causes the curve to break.

Figure 4.5-11 illustrates the "multiplier effect" of inert weight reductions in propulsion elements. The relative program cost improvement resulting for 50% cost reductions in propulsion elements with no weight change, at $0.7 billion, is small compared to the resulting $5.1 billion when stage inert weights are reduced 50% with no cost change.

Research Implications

Structural research implications of the study place an emphasis on ERV-SMM weight reductions, improvements in MEM performance, and increases in propulsion-stage mass fractions.

The demonstrated $160,000/lb weight sensitivity of the ERV-SMM indicates that weight reductions can and must be made for these vehicles. Very high levels of structural sophistication can be justified with this marginal cost. The implications of this sensitivity are probably even more important to other subsystems than to structure because they are not as well developed.

Well over $1 billion is available to justify MEM weight-improvement research. Research should be concentrated on using high-density high-energy propellants and on a better understanding of the Martian atmosphere so that maximum use can be made of aerodynamic deceleration. Low-velocity deceleration systems, such as parachutes, for the Martian atmosphere should be pursued further.

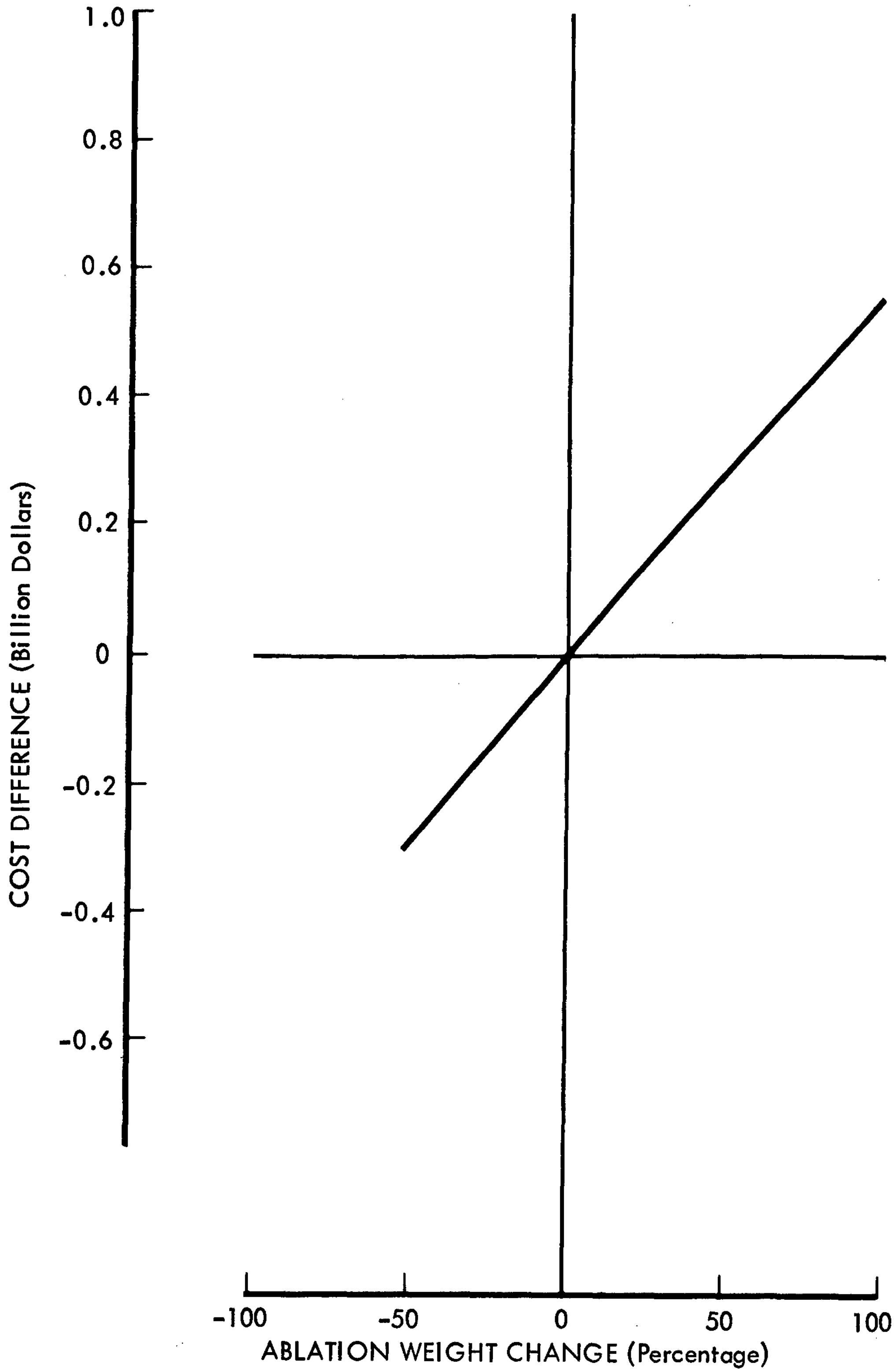


Figure 4.5-9: PROGRAM COST SENSITIVITY TO PLANETARY AEROBRAKING STAGE THERMAL PROTECTION WEIGHT

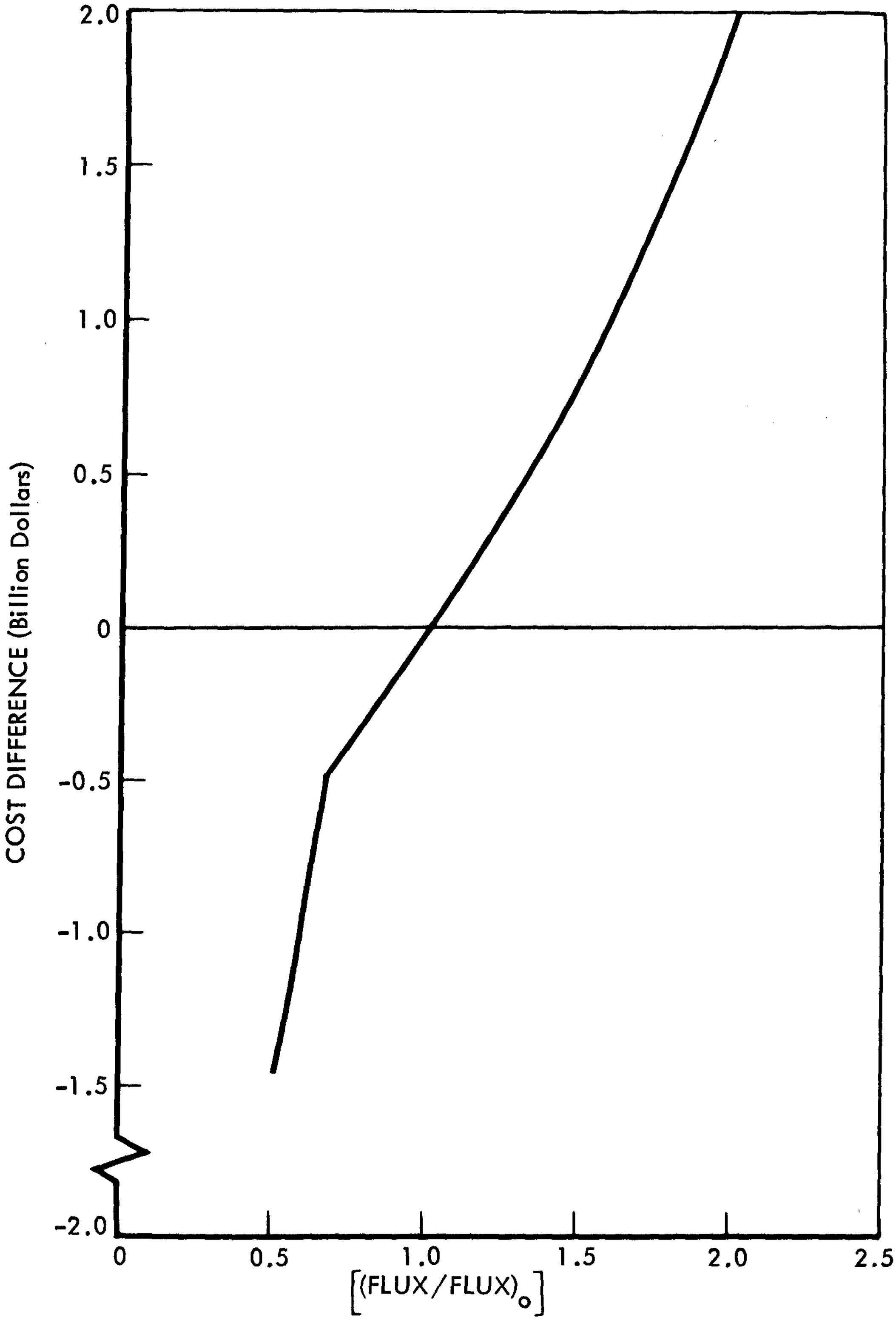


Figure 4.5-10: PROGRAM COST SENSITIVITY TO METEOROID FLUX

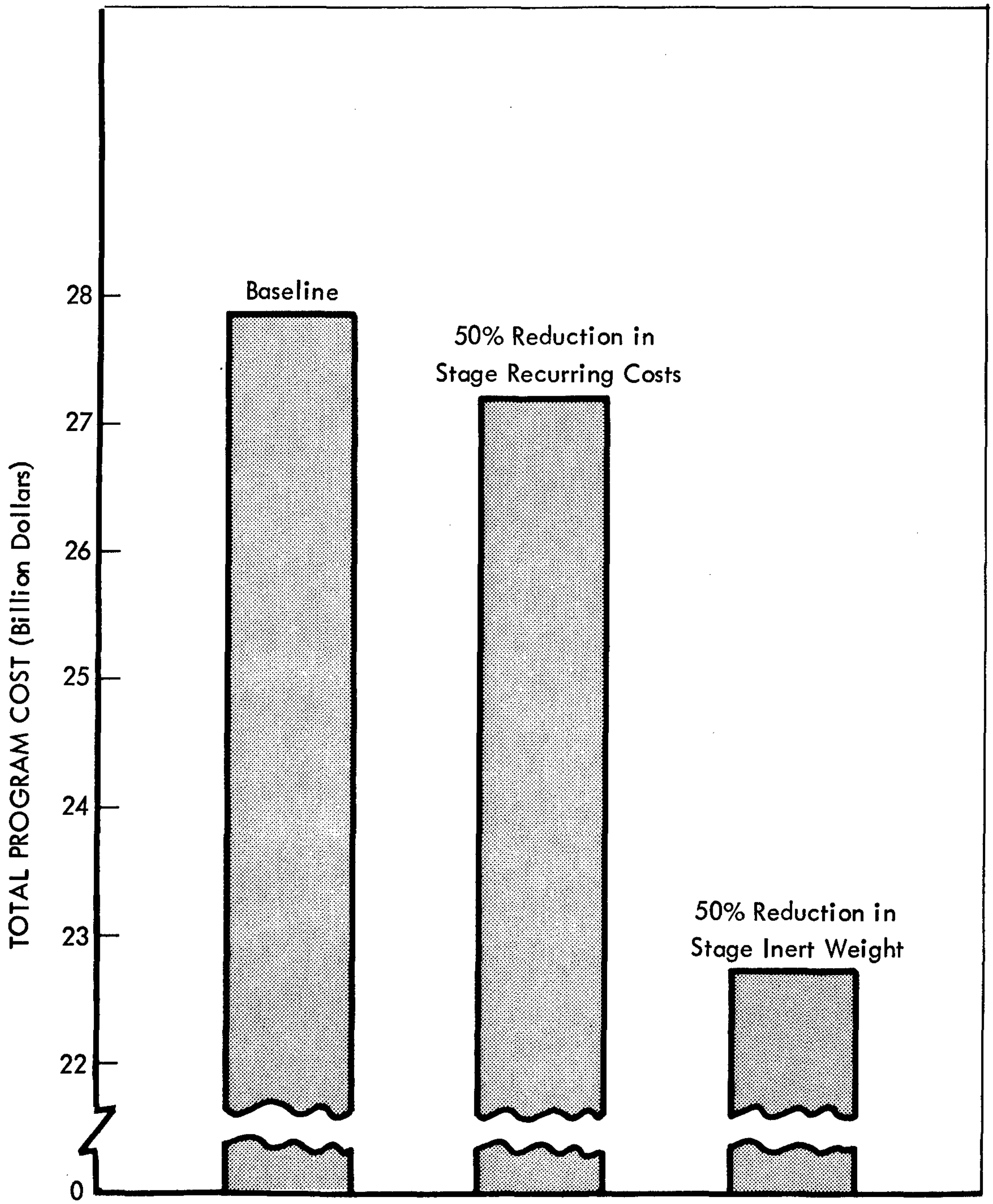


Figure 4.5-11: COMPARISON OF COST AND WEIGHT IMPROVEMENT IN SPACE PROPULSION MODULES

Improvements in space propulsion stage mass fractions are of paramount importance in Mars lander missions. Structural research aimed at high-efficiency meteoroid shielding is particularly powerful. Improved materials or configurations and a better understanding of the meteoroid environment are specifically required. Reductions in tank structural weight, accomplished by improved materials, although not as important as meteoroid shield improvements, should receive attention. Current technology in cryogenic insulations appears adequate for Mars missions, with the reservation that the feasibility of these applications be demonstrated.

Significant advantage for low-weight ablation (or radiation) aerobraking thermal protection is demonstrated, first by the $1.7 billion cost reduction shown for Concept 4 over Concept 2 and, second, by the further cost reductions available through improved materials. Ablation material technology is advancing, and a better understanding of the behavior of these materials in the Martian atmosphere will permit more specific recommendations for the use of planetary aerobraking.

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